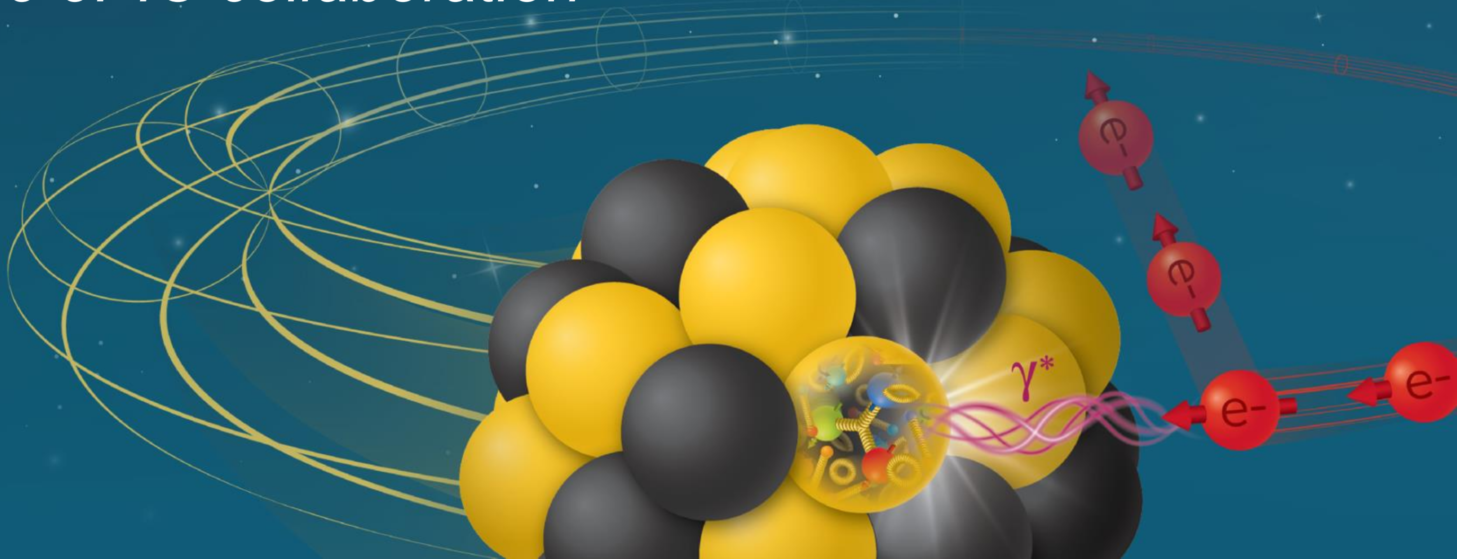
Technologies for ePIC Far-Forward Detectors and Other Applications

Alex Jentsch (BNL) *on behalf of the ePIC collaboration*

Synergies between LHC and EIC
Krakow, Poland
September 21st to 24th, 2025

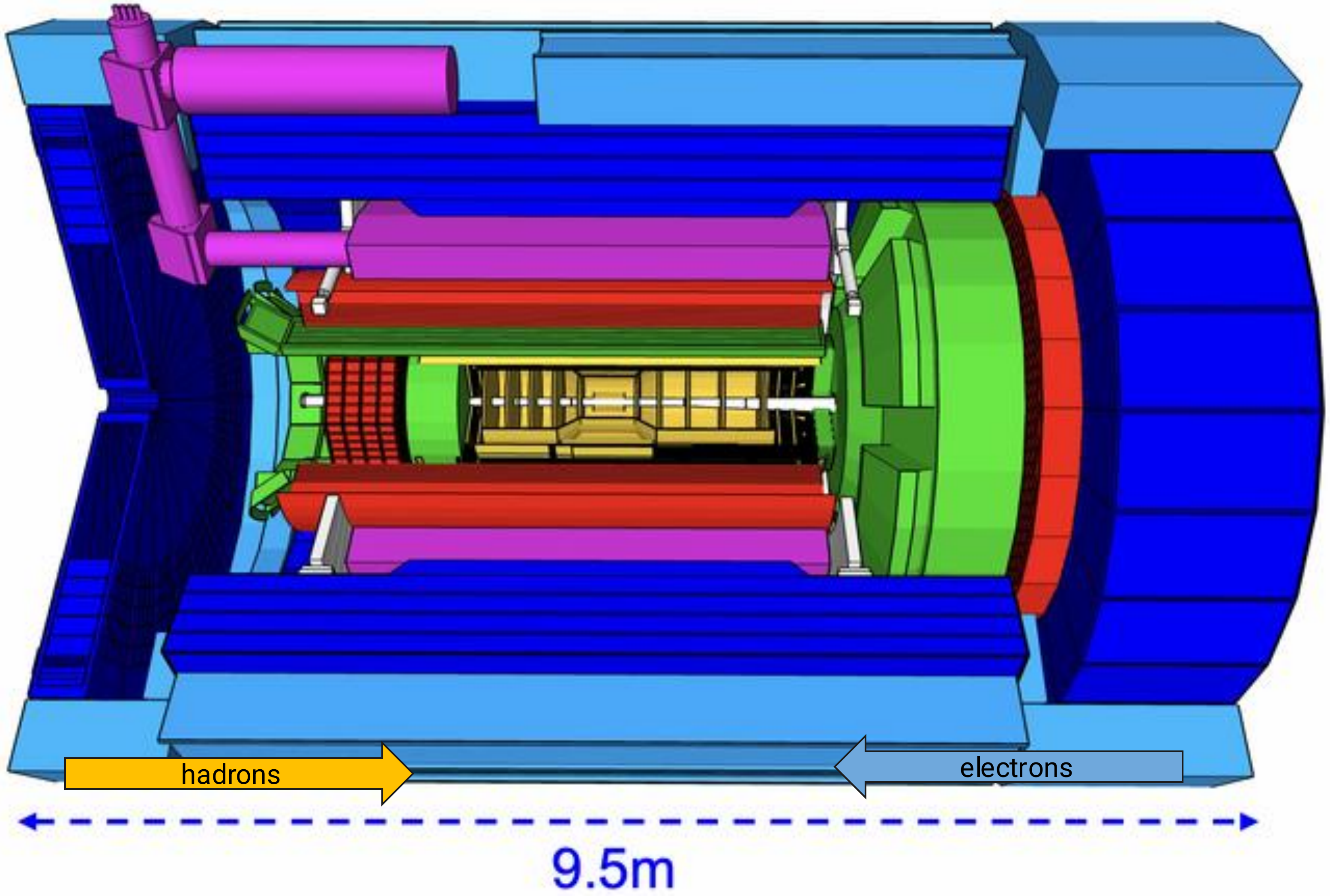
Electron-Ion Collider



The ePIC Detector

hadronic calorimeters | solenoid coils | e/m calorimeters

MAPS tracker | MPG trackers | ToF, DIRC, RICH detectors



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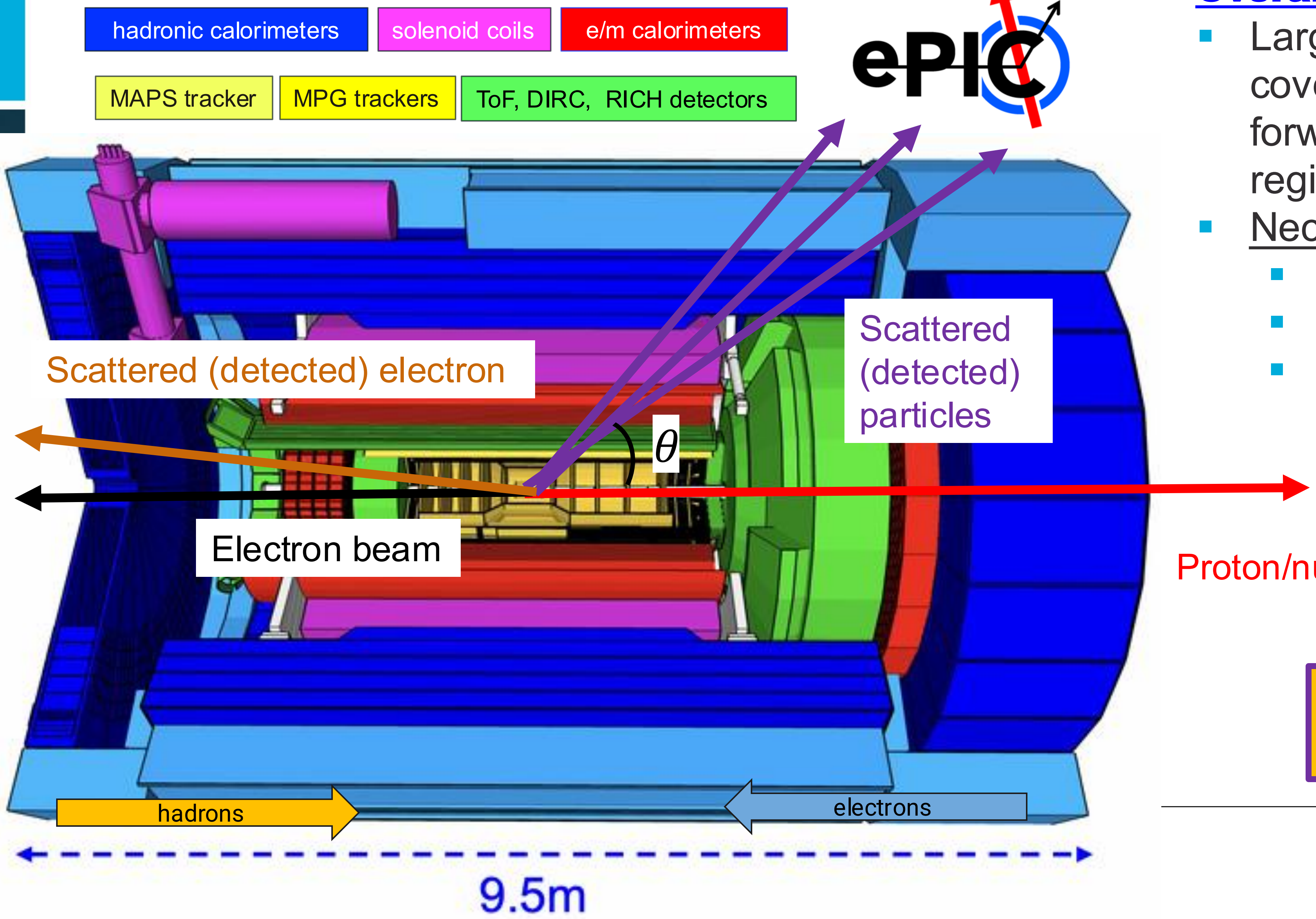
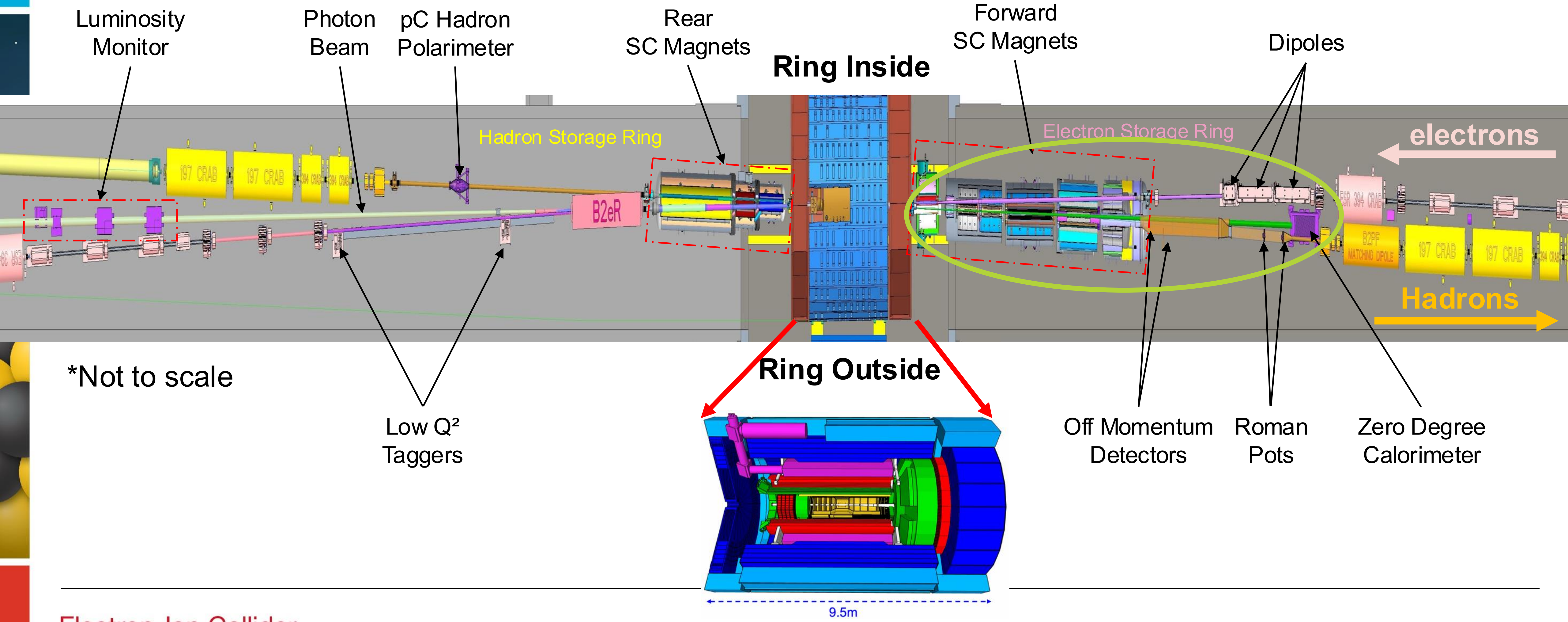


Overall detector requirements:

- Large rapidity (-3.5 < h < 3.5) coverage; and far beyond in far-forward/far-backward detector regions.
- Necessity for:
  - High-resolution tracking.
  - EM and hadronic calorimetry.
  - PID over a very broad momentum range.

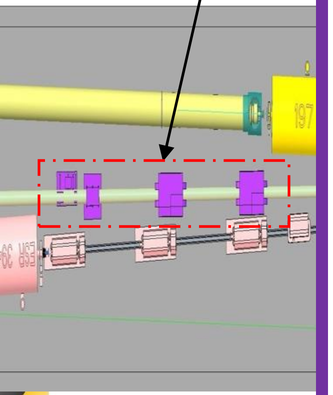
See talk from Brian on the larger ePIC detector.

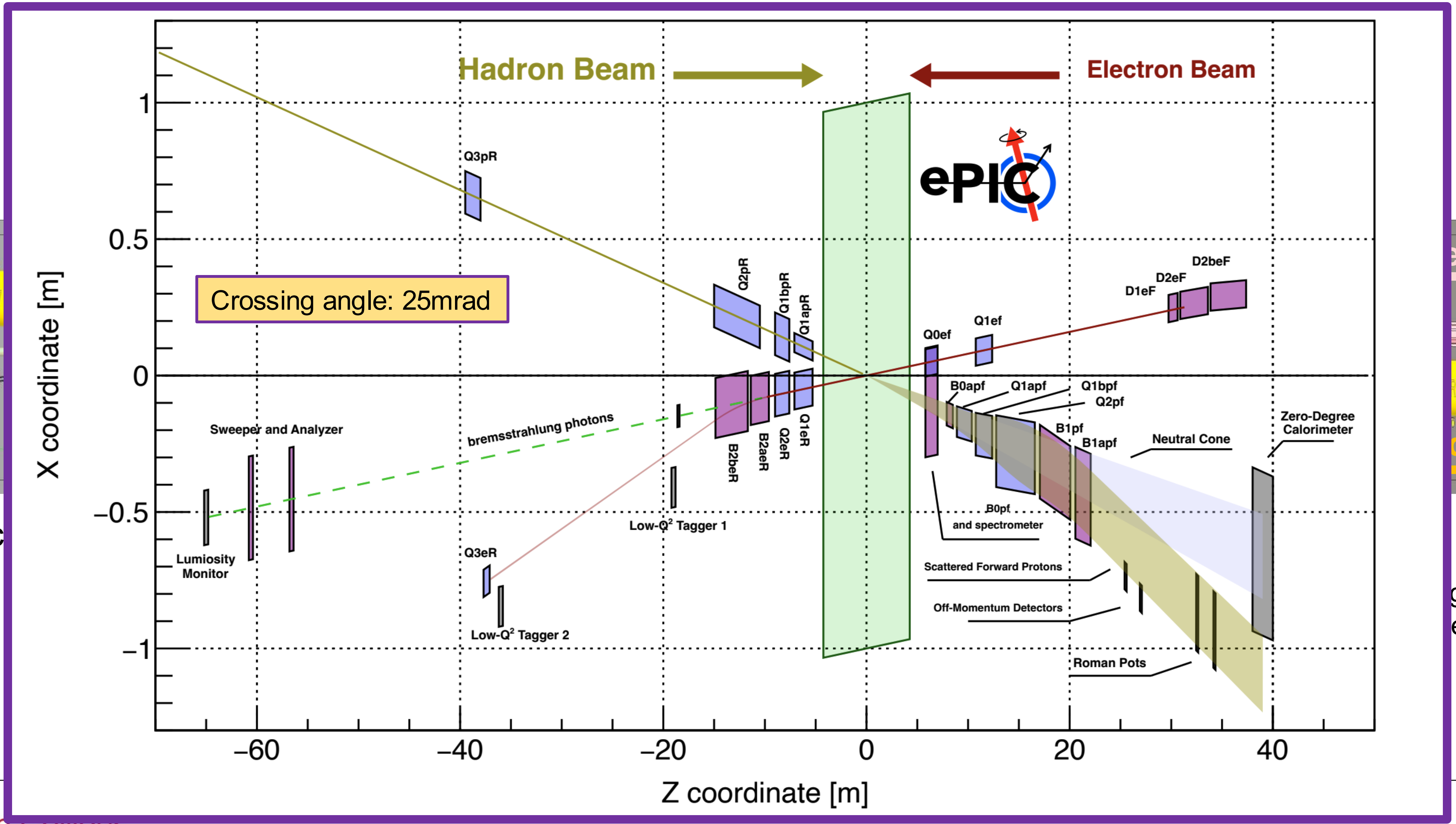
ePIC Far-Forward Detectors

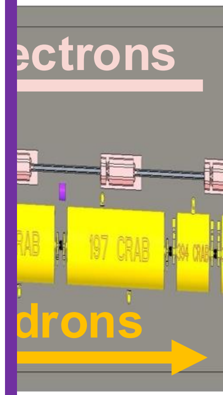


ePIC Far-Forward Detectors

Luminosity Monitor







*Not to sc

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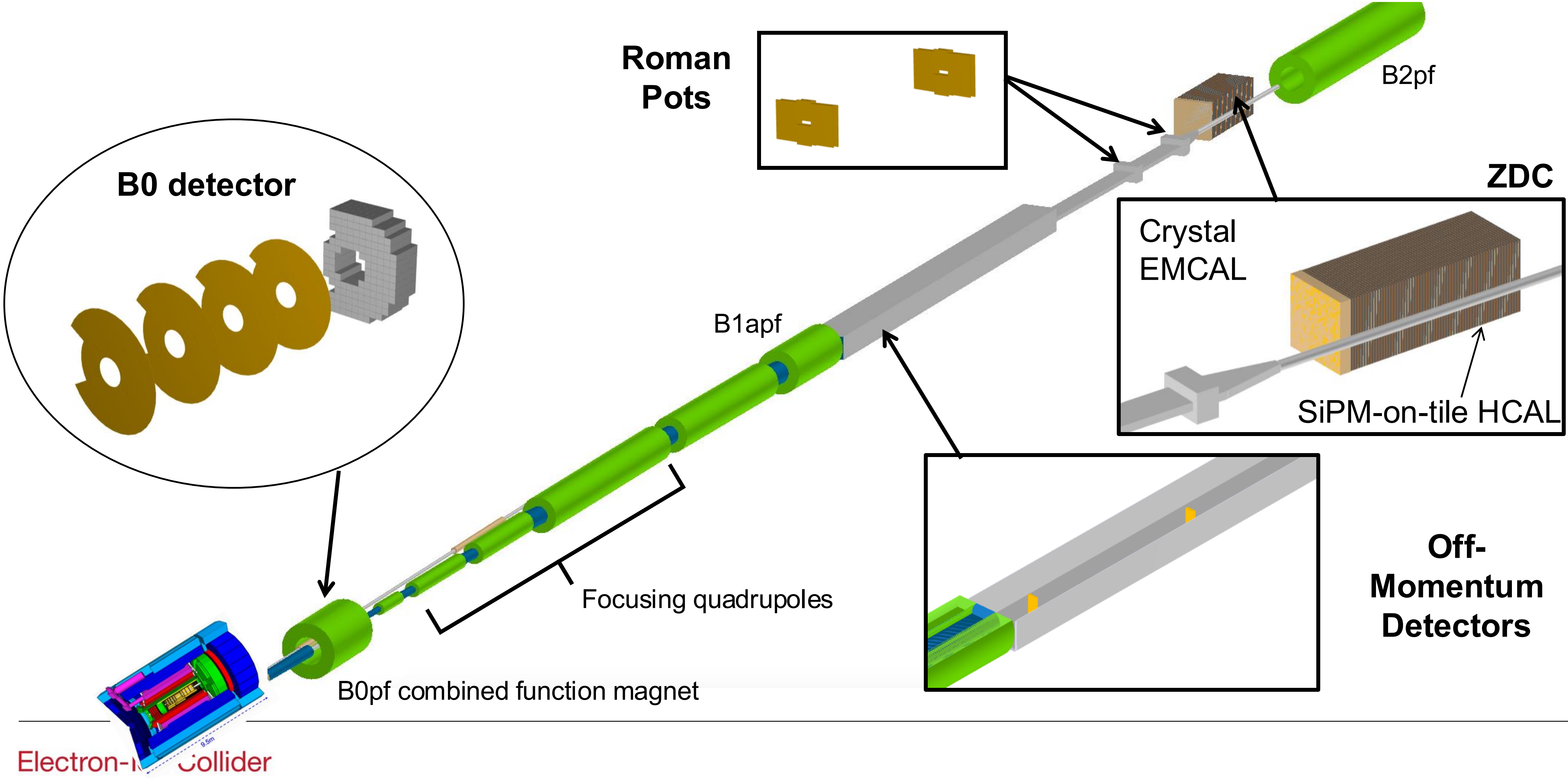
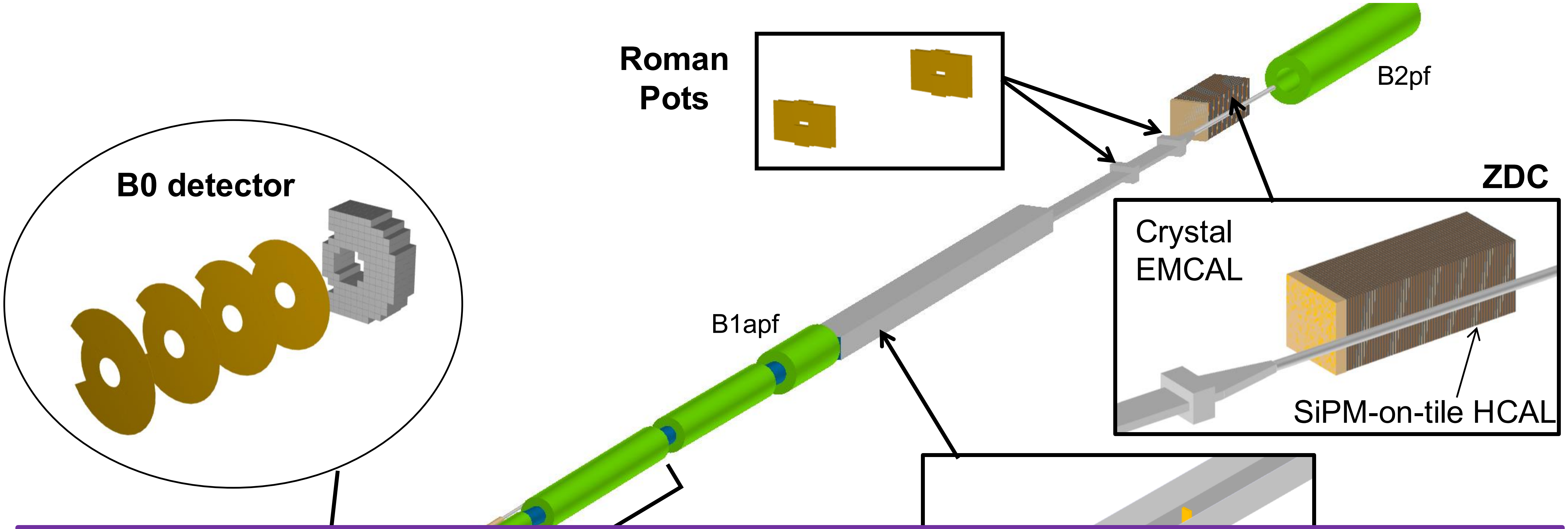
ePIC Far-Forward Detectors

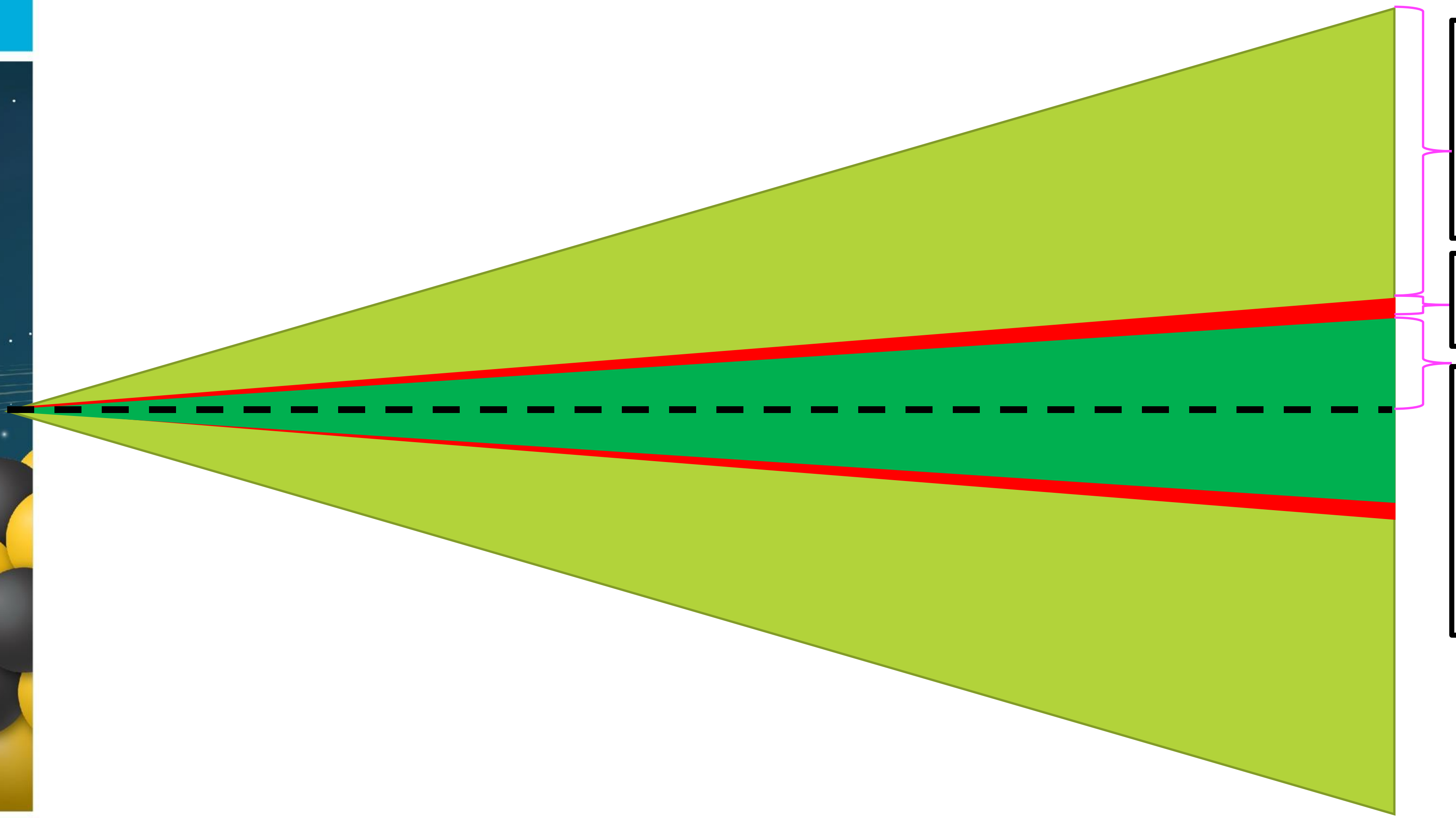


ePIC Far-Forward Detectors



- All tracking detectors comprised of **AC-LGAD** silicon (also used in time-of-flight system and luminosity detector).
- EM calorimetry is $PbWO_4$ crystals (same as elsewhere in ePIC).
- ZDC HCAL is **Fe/scintillator with embedded SiPMs** (same as HCAL insert) in etched cells in the scintillator to provide shower imaging information.

ePIC Far-Forward Detectors



5.5 < θ < 20 mrad (**B0 detector**)

Detector acceptance starts at 5.5 mrad, and ends a little higher than 20 mrad (still TBD as design matures). Only 13mrad on one side of the detector due to electron beam line.

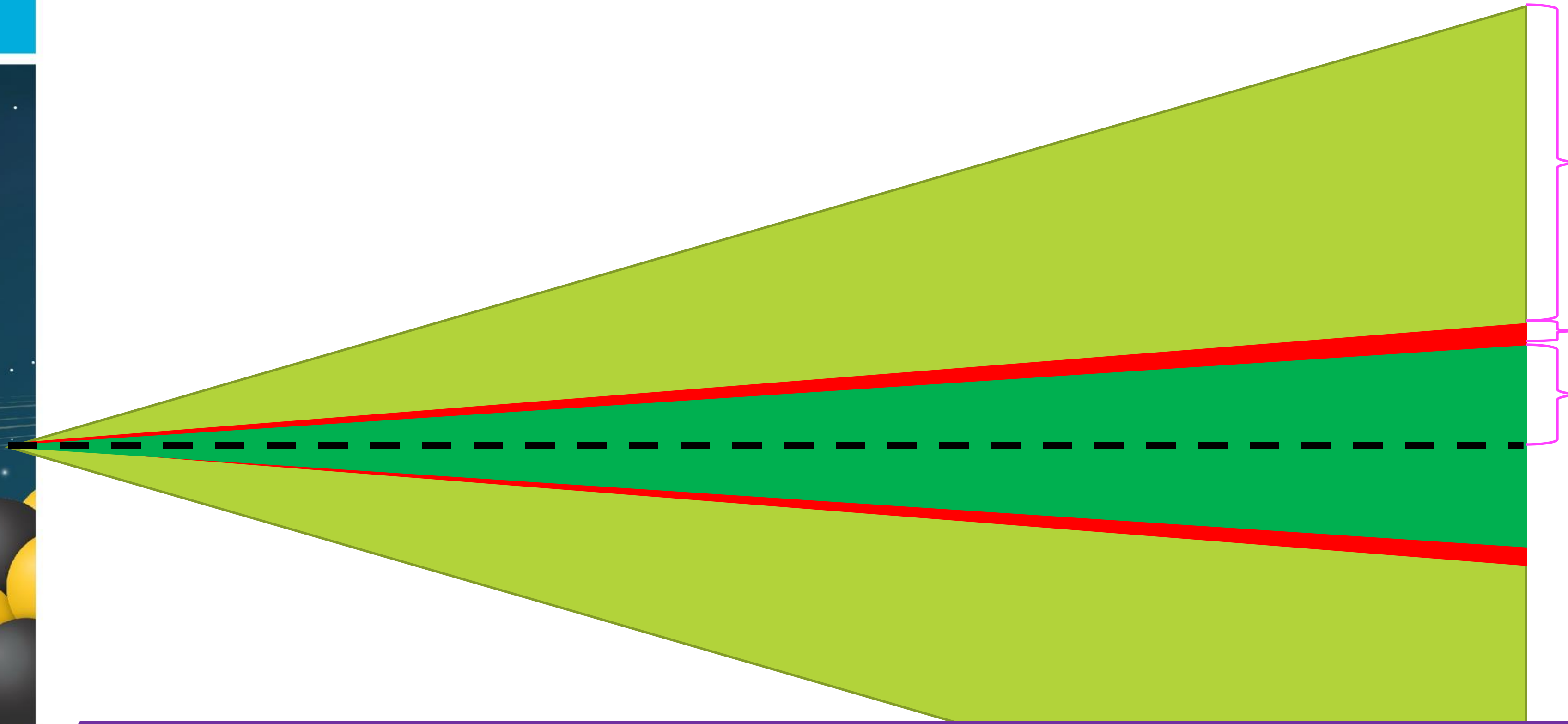
5.0 < θ < 5.5 mrad

Acceptance gap between B0 and other FF detectors.

0 < θ < 5 mrad (**roman pots, OMD, ZDC**)

Upper limit comes from aperture. Neutrons aren't bent in magnetic field, but protons will hit different detectors based on their p_z with respect to the beam momentum.

ePIC Far-Forward Detectors



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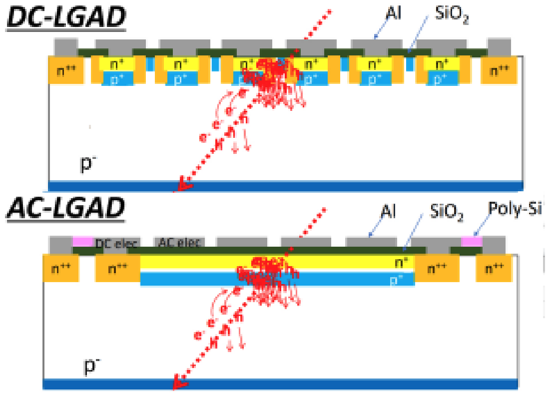
- **<u>Enables (virtually) the entire EIC exclusive physics program.</u>**
  - DVCS, exclusive VM production, tagged DIS from light nuclei (e.g. neutron structure functions), pion/kaon form factors, u-channel DVCS and VM production, etc. (the list is long).

Basic Requirements for FF Subsystems

- Comprehensive tables of requirements + references can be found here: https://wiki.bnl.gov/EPIC/index.php?title=FarForward
- **Tracking requirements:**
  - Spatial resolution < 20um for B0 spectrometer (< 140um for the Roman pots/off-momentum detectors).
  - Timing resolution ~ 35ps to disentangle crossing angle effects.
- **Calorimetry requirements:**
  - B0 EMCAL → $\frac{\sigma_E}{E} < 20\% \oplus 3\%$, spatial resolution < 1-2cm, sensitivity to photons ~ 100 MeV.
  - ZDC EMCAL(s) → $\frac{\sigma_E}{E} < 20\% \oplus 3\%$, sensitivity to ~ 100 MeV photons, $\frac{\sigma_\theta}{\theta} < \frac{2\,mrad}{\sqrt{E}}$
  - ZDC HCAL → $\frac{\sigma_E}{E} < 35-50\% \oplus 3-5\%$, $\frac{\sigma_\theta}{\theta} < \frac{2\,mrad}{\sqrt{E}}$

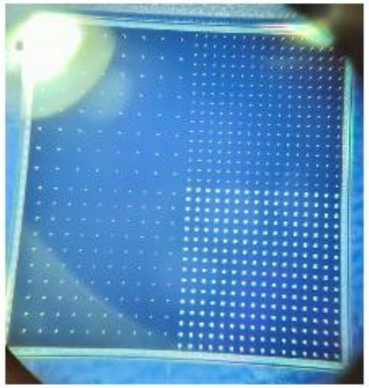
Two primary new technologies for ePIC FF

- AC-coupled Low Gain Avalanche Diodes (AC-LGADs)
  - AC-LGADs allow for fine pixelization + charge sharing.



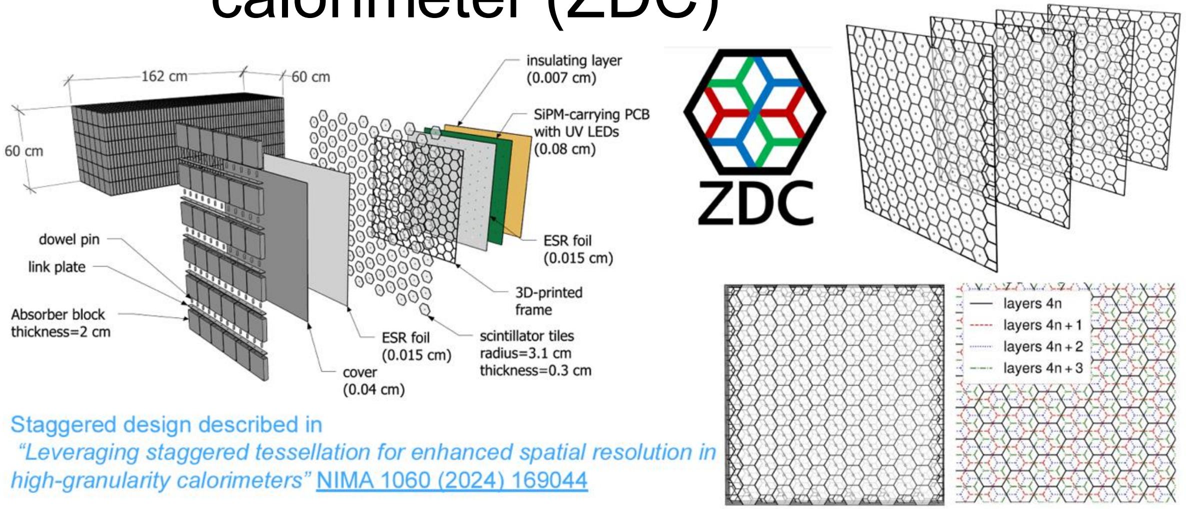
Sayuka Kita, Koji Nakamura, Tatsuki Ueda, Ikumi Goya, Kazuhiko Hara, NIMA **1048**, 168009 (2023)

ePIC full size pixel detector: 1.6x1.6cm



Also used in ePIC time-of-flight subsystems and luminosity detector.

- SiPM-on-tile sampling/imaging calorimeter (ZDC)



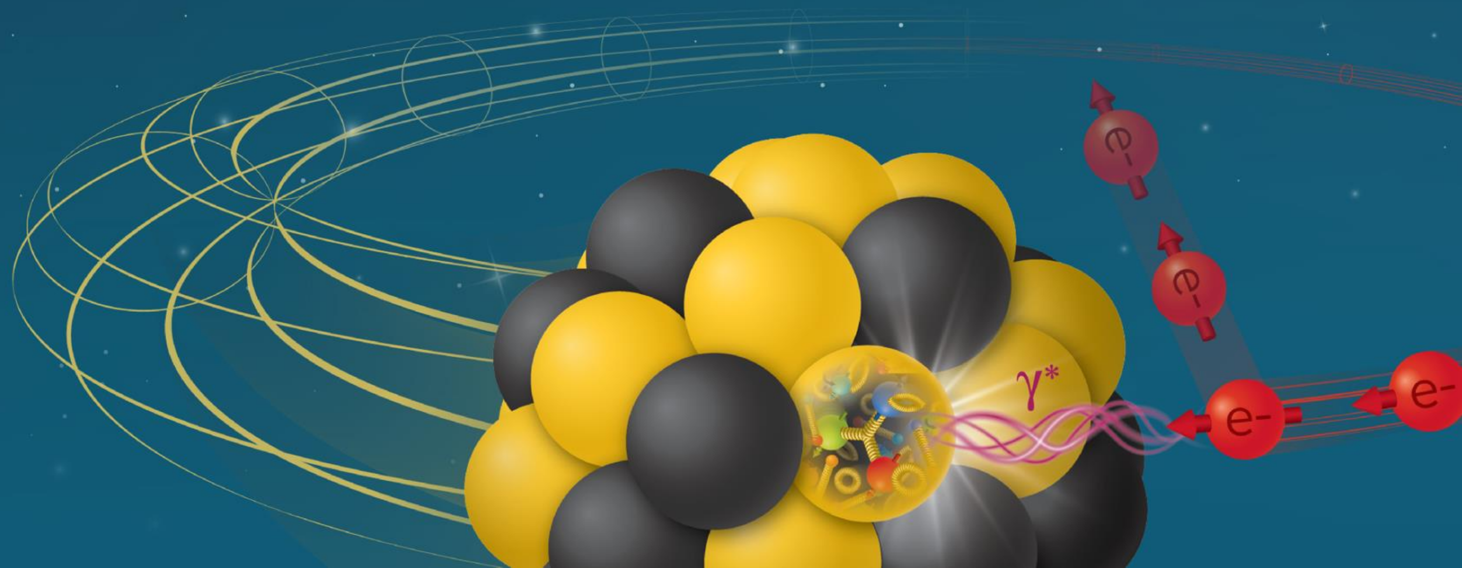
Staggered design described in "Leveraging staggered tessellation for enhanced spatial resolution in high-granularity calorimeters" NIMA 1060 (2024) 169044

2 cm of iron = 1.1 X_0

These technologies meet the performance requirements of the far-forward subsystems.

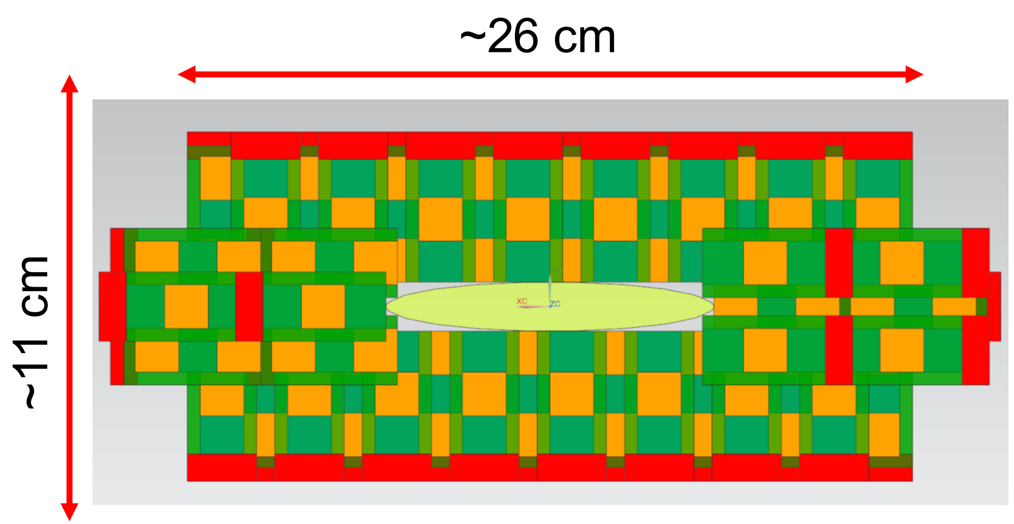
Also used in high-pseudorapidity portion of forward EMCAL in main detector.

More detail on FF detector designs



Electron-Ion Collider

Roman pots (and Off-Momentum Det.)



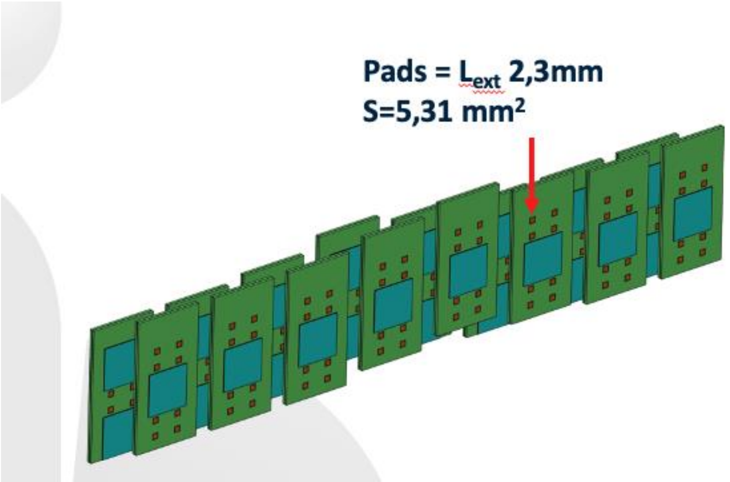
$\sigma(z)$ is the Gaussian width of the beam, $\beta(z)$ is the RMS transverse beam size.
ε is the beam emittance.

$$\sigma(z) \sim \sqrt{\varepsilon \cdot \beta(z)}$$

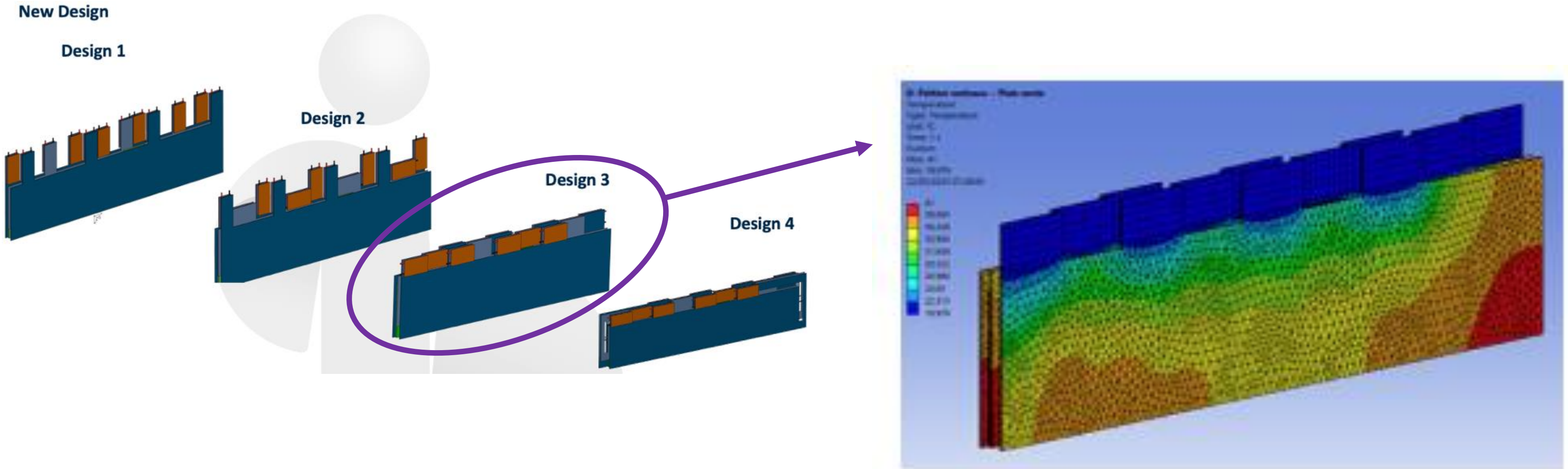
- **<u>Low-pT cutoff determined by beam optics.</u>**
  - The safe distance is ~10σ from the beam center (1$\sigma \sim$ 1mm).
- **<u>Optics change with energy</u>**
  - Can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity*.
- Able to achieve spatial and timing requirements without charge sharing – 500um pixels work "out of the box".

- Two layers of sensors, organized into two stations each.

Roman pots (and Off-Momentum Det.)

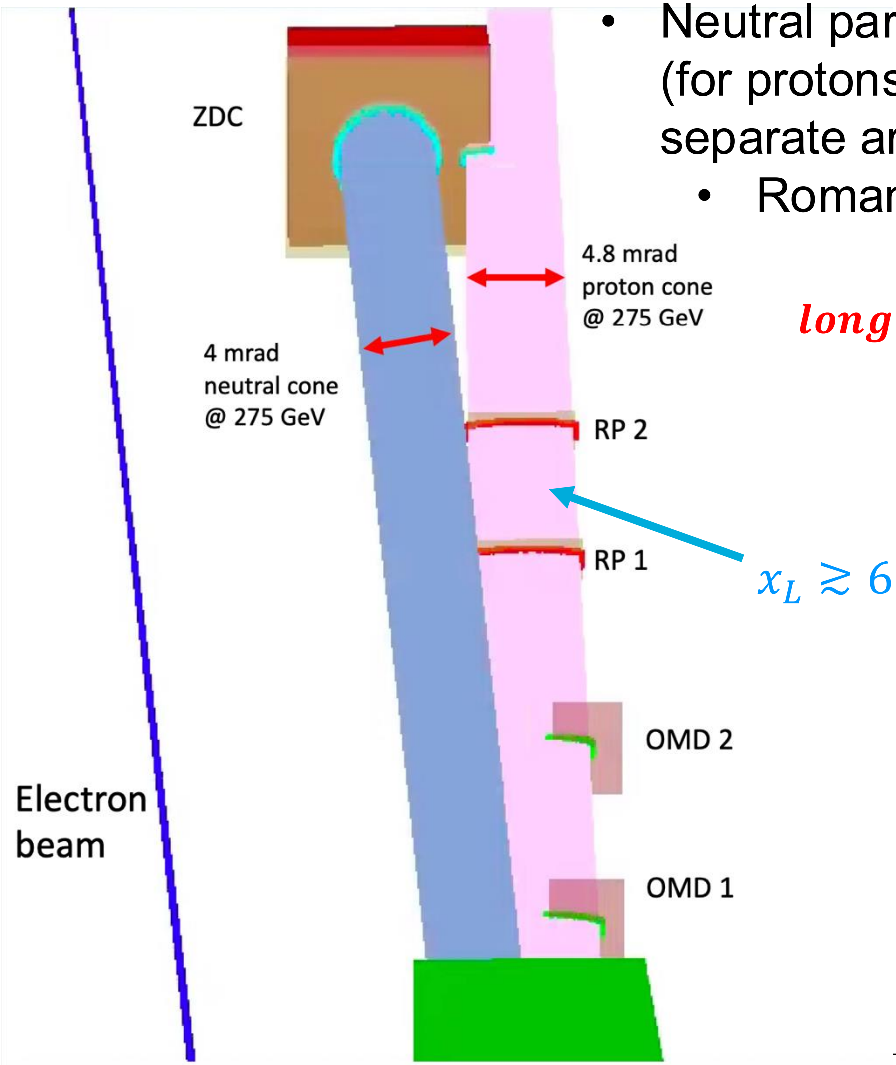


- Cooling of detector *in-vacuum* a major concern → ~ 100 Watts per-layer of sensors (from ASIC).
  - IJCLab providing mechanical eng. to design cooling system using pads with Peltiers (effects of radiation environment on Peltiers at RP need to be understood).
- All packages thermally coupled to outside via support structure, coupled to a chiller in the tunnel.



	P_{Asic} (W)	$T_{Peltier}$ (°C)	T_{max} (°C)
Design 3	2,048	20	41
		10	31
		0	21
		-10	11
	1,024	20	30,5
		10	20,5
		0	10,5
		-10	0,5

Roman pots (and Off-Momentum Det.)



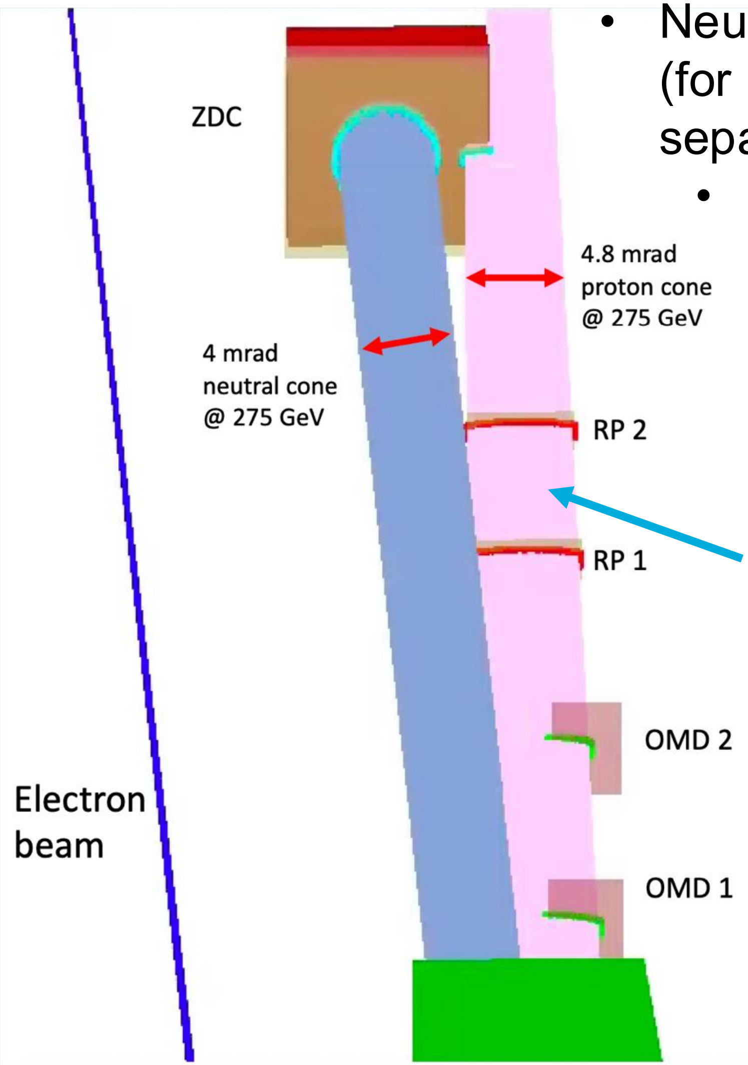
- Neutral particle cone and proton cone (for protons with p ~ beam momentum) separate around 30m from the IP.
    - Roman pots placed in this region.

longitudinal momentum fraction

$$x_L = \frac{p_{z,proton}}{p_{z,beam}}$$

$x_L \gtrsim 65\%$

Roman pots (and Off-Momentum Det.)



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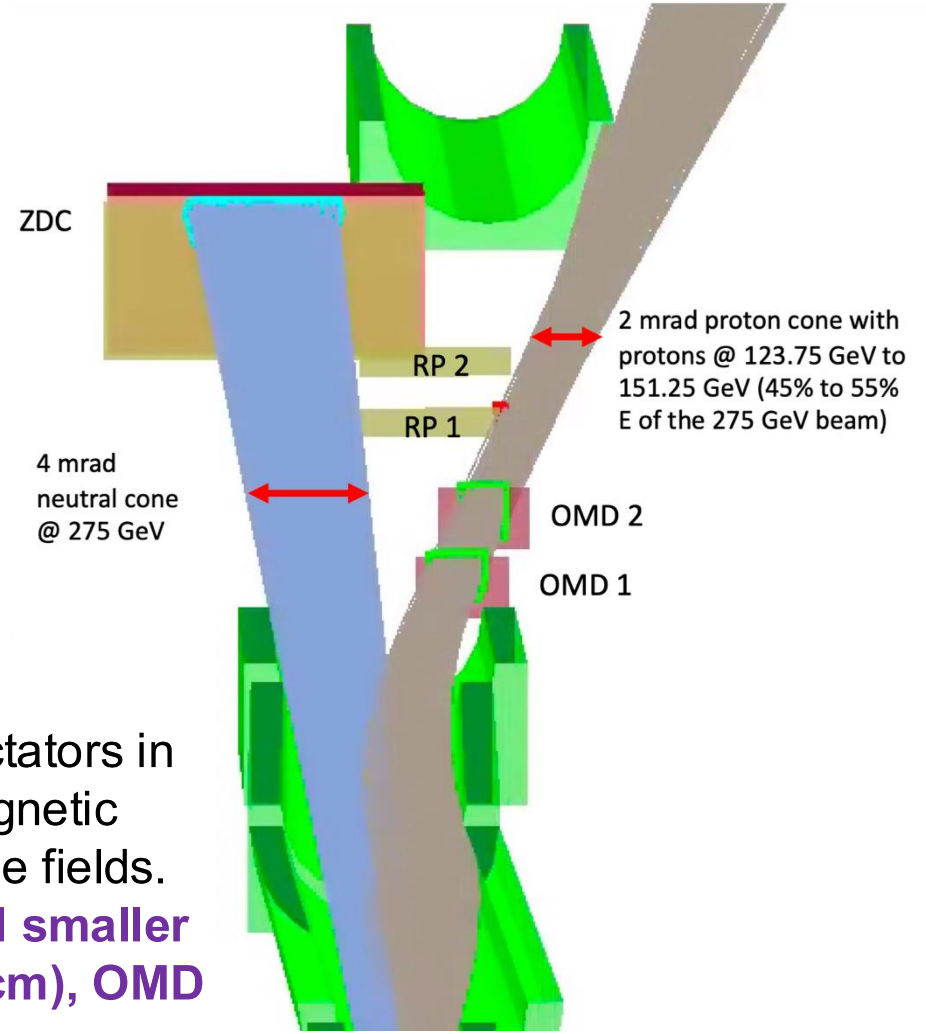
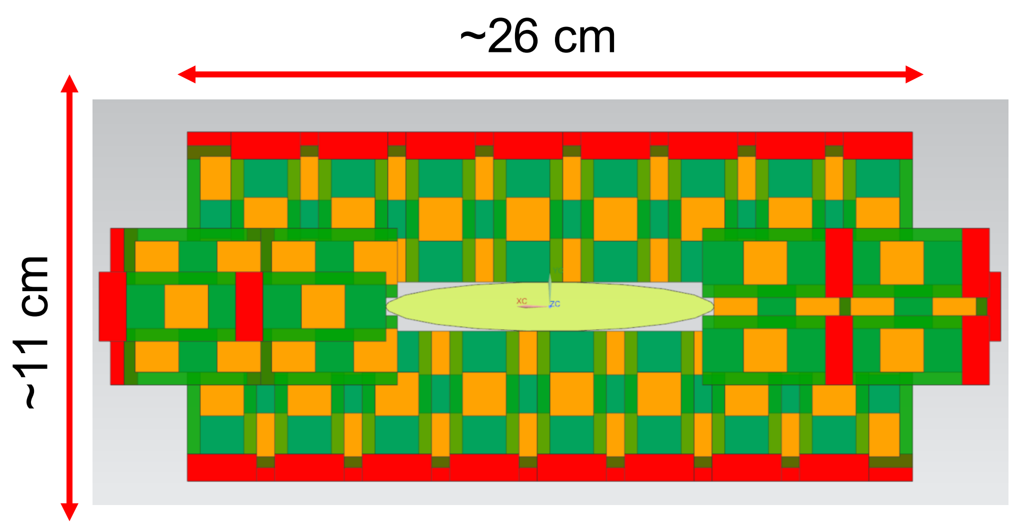
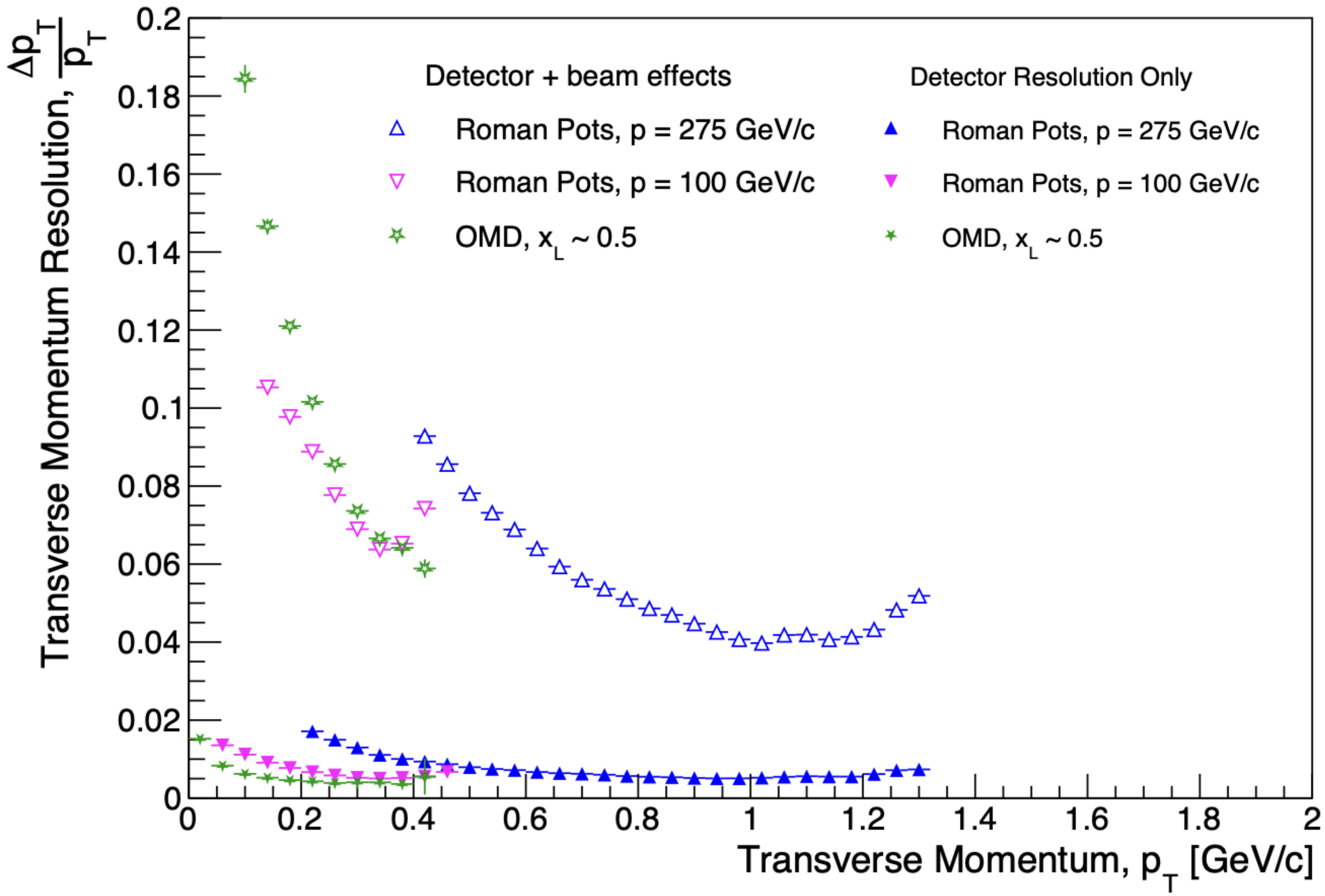


- Off-momentum protons (e.g. spectators in deuteron breakup) → smaller magnetic rigidity → greater bending in dipole fields.
  - **Other than the location and smaller package size (~ 10cm x 20cm), OMD are identical to the RP.**

Roman pots (and Off-Momentum Det.)

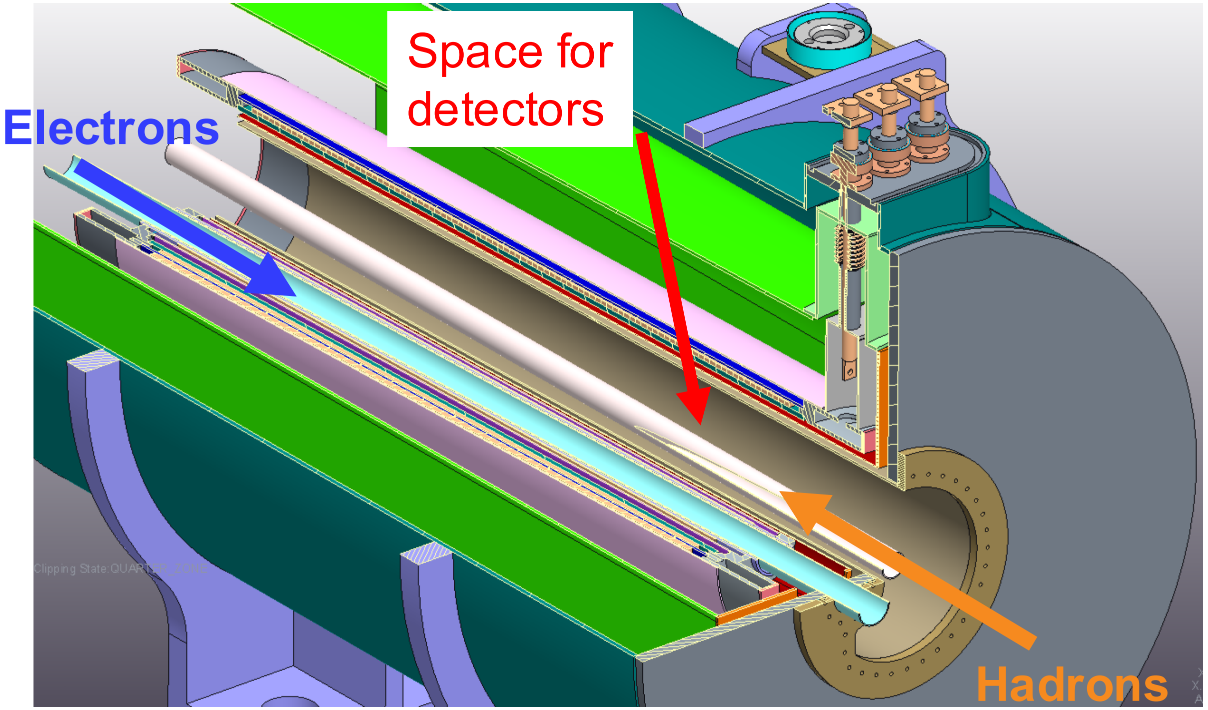


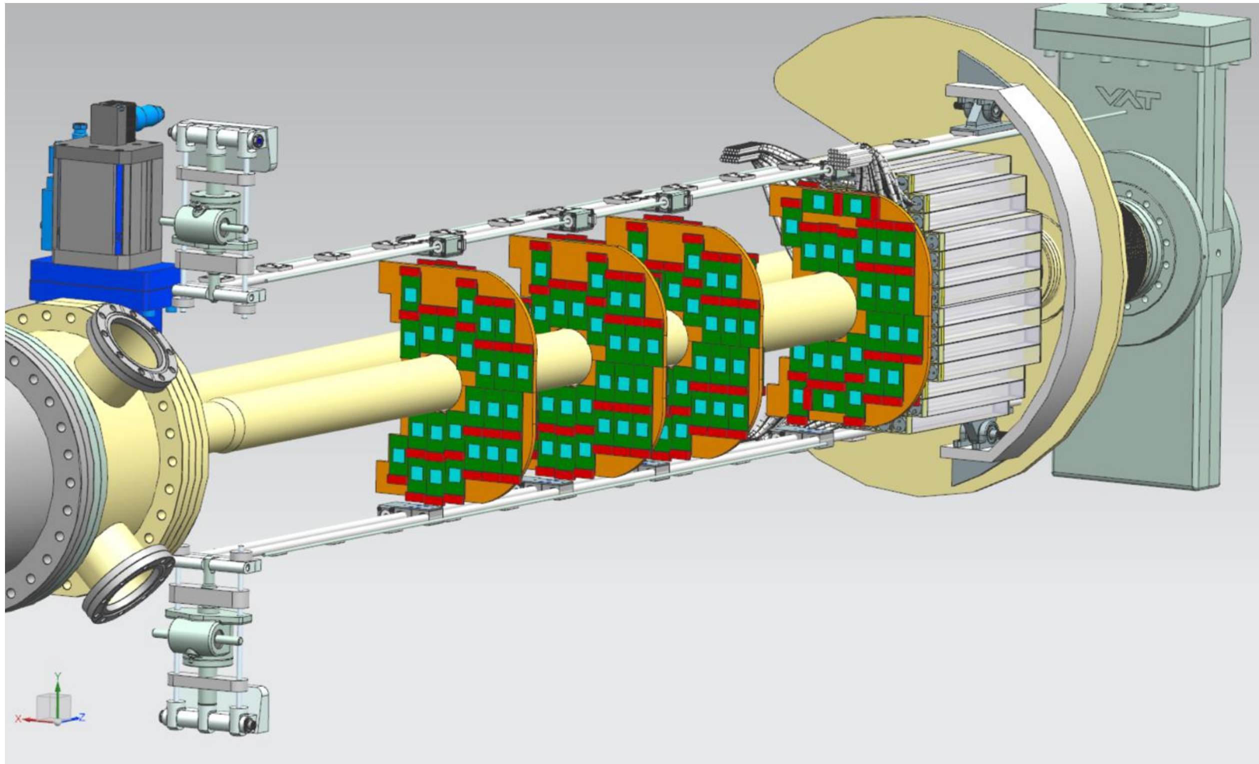
- All simulations include both detector effects (e.g. pixel size and material budget), and beam effects (e.g. angular divergence).
- **Beam effects have largest impact on resolution for the far-forward detectors.**



B0 Detectors

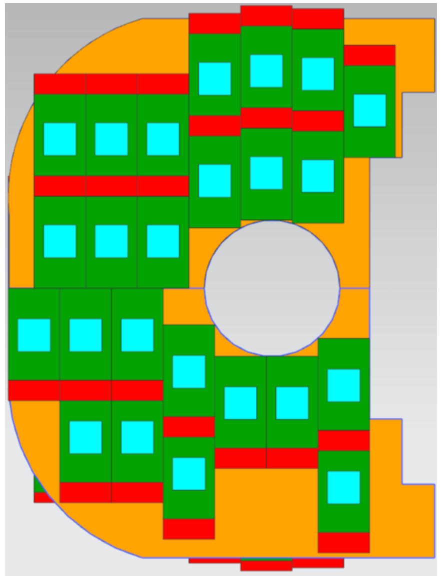
➢ Detector subsystem(s) embedded in an accelerator magnet.

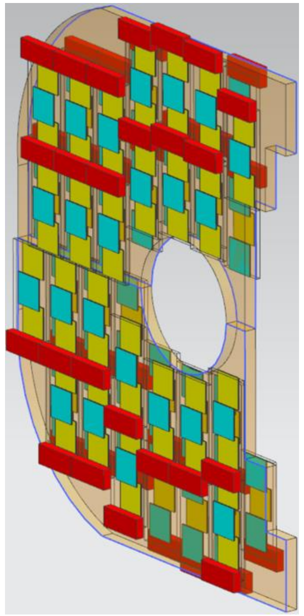


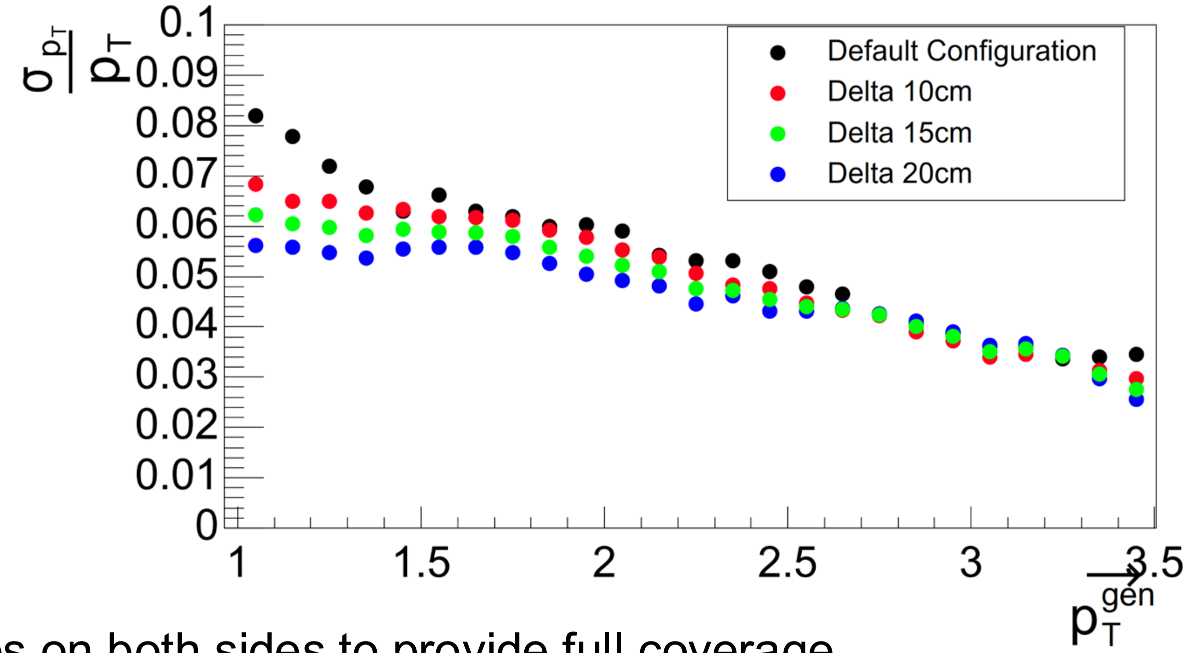


- **Two detectors**:
    - AC-LGAD based silicon tracking detector.
    - PbWO4 EM calorimeter (same crystals used elsewhere in ePIC)
- Primary challenges are related to integration with the machine (detector fully embedded in machine dipole magnet) and achieving required performance of tracking detector.

B0 Detectors - Tracker

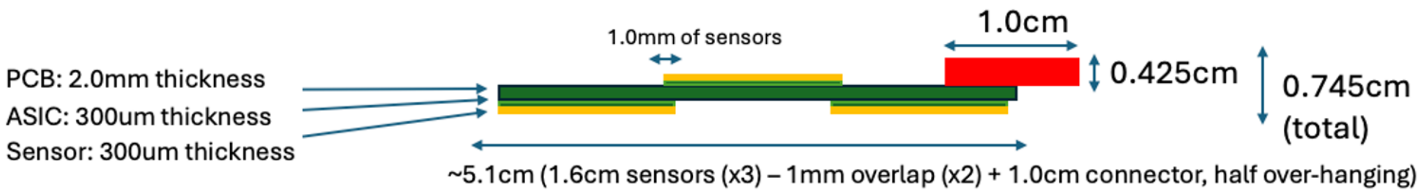


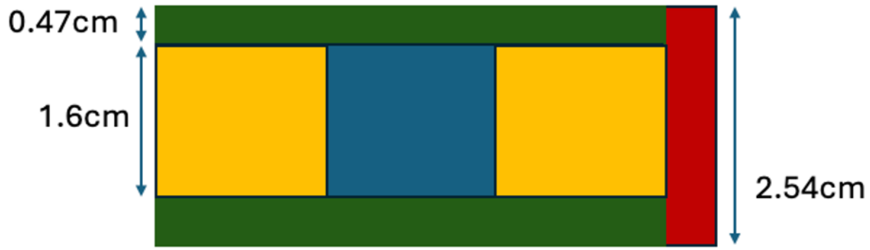


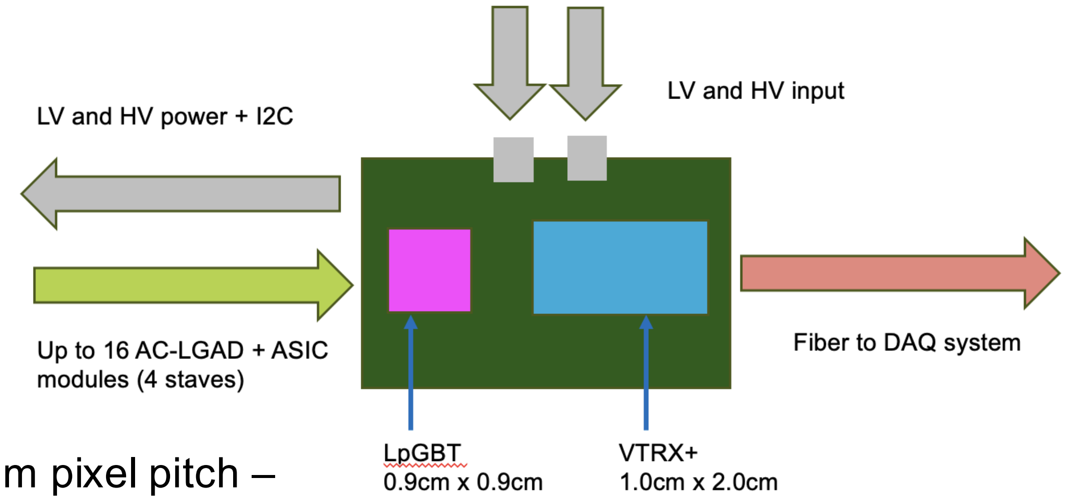


- ”Disks” populated with FF AC-LGAD staves on both sides to provide full coverage.
- p_T resolution driven by AC-LGAD spatial resolution, and placement of the detector within the B0 magnetic field (inhomogeneous) → Shifting of the tracking system toward center improves resolution.
  - Performance of full AC-LGAD + EICROC needs to be carefully evaluated for spatial resolution with charge sharing.
- Cooling will be done using air circulation with capillaries integrated into the disks → design underway.
  - Liquid cooling provide significant additional risk and challenges for maintenance.

AC-LGADs for FF Tracking







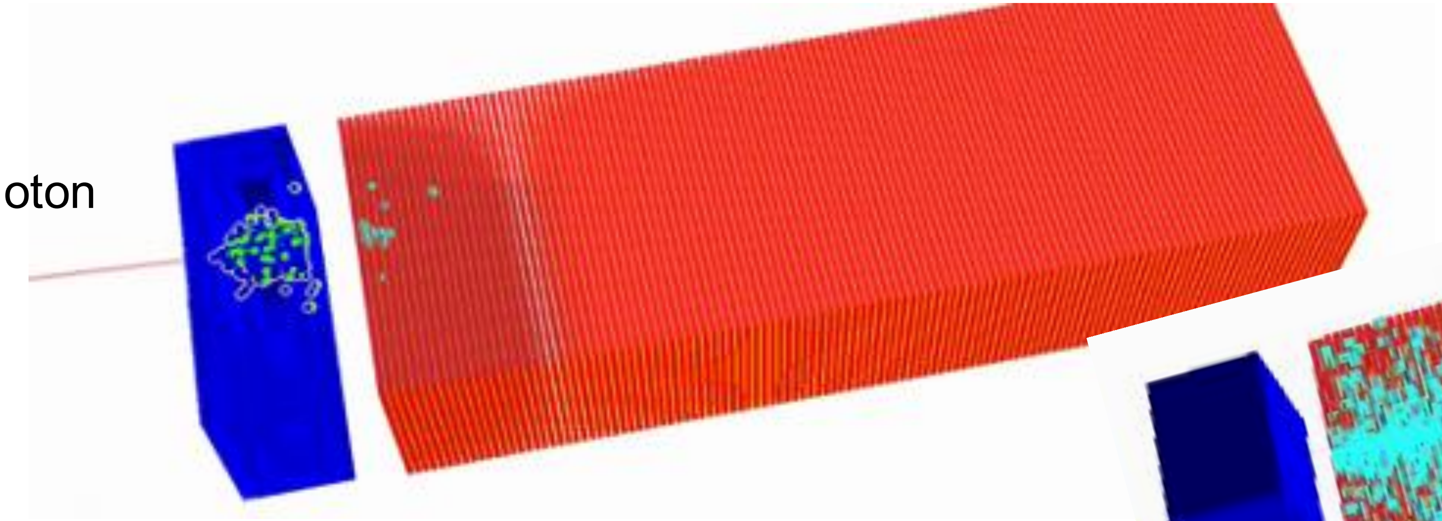
- Sensor “staves” will have three 1.6cm x 1.6cm AC-LGADs with 500um pixel pitch – bump-bonded to **EICROC ASICs****, staggered on a two-sided PCB to provide full active-area coverage.
  - These sensors have 32x32 channels, matching the EICROC.
- Sensors, ASICs, and Front-end readout/power will share design with the Forward TOF → only difference is sensor stave/module, and the separation of the FEB for flexibility for FF detector needs.
- Stave dimensions will be updated once EICROC1 schematic is in-hand.

**EICROC is a new ASIC specifically for the pixilated AC-LGADs in ePIC.

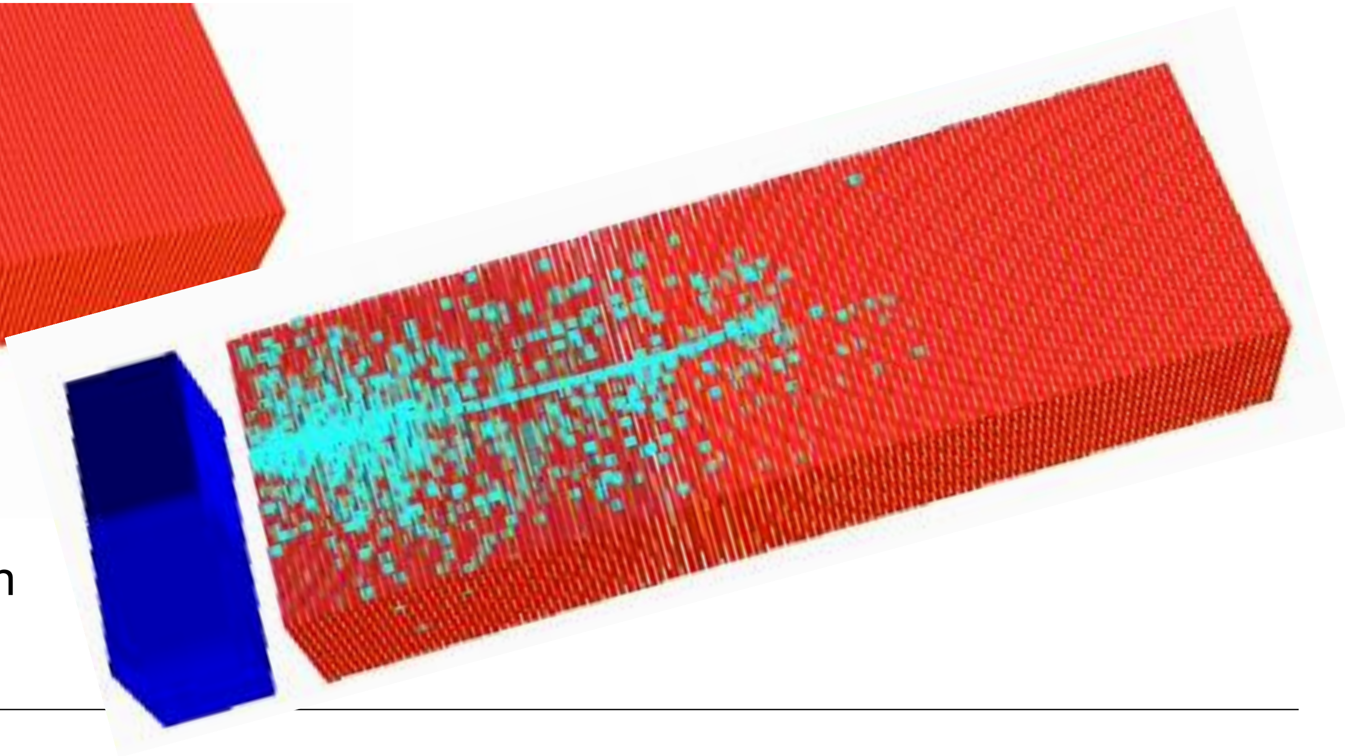
Zero-Degree Calorimeter

- Need a calorimeter which can accurately reconstruct photons and neutrons from our various final states (e.g. e + d tagged DIS, incoherent vetoing in e+A, backward u-channel omega production).
- Need an HCAL with high energy resolution and postion resolution, and an EMCAL with a wide dynamic range (100 MeV to 100 GeV).

photon

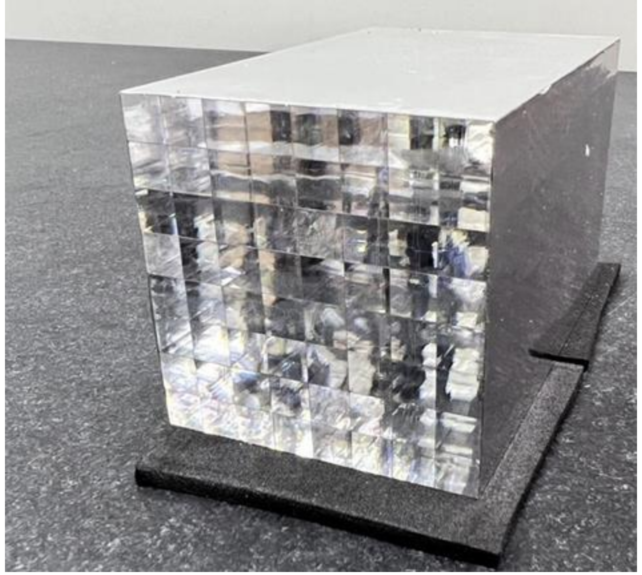


neutron



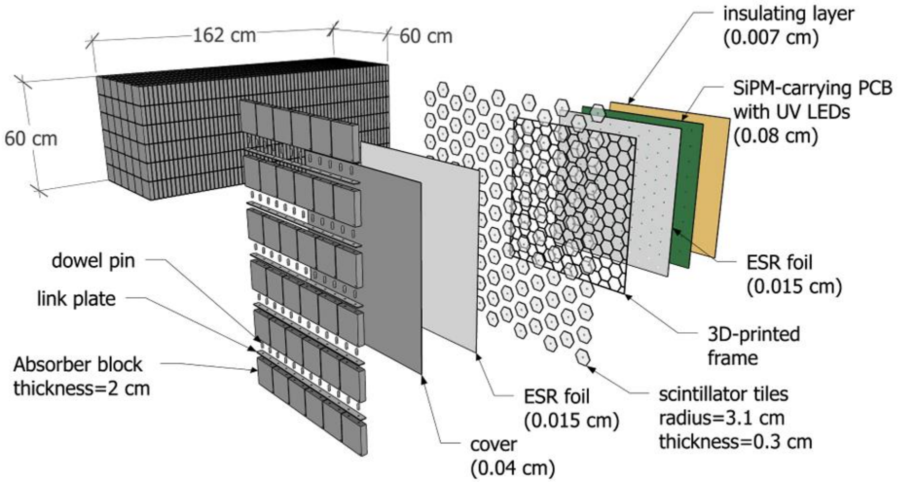
Zero-Degree Calorimeter

EM Calorimeter – PbWO4



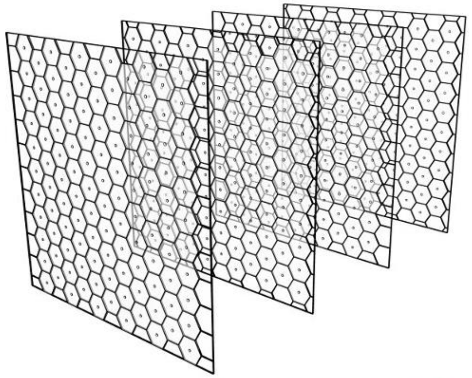
crystal array with 2x2x7cm crystals.

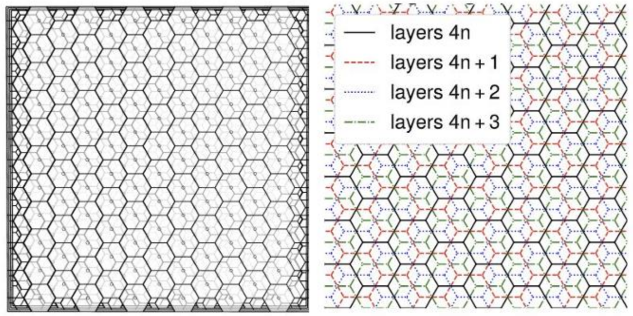
Hadronic Calorimeter – SiPM-on-Tile



Staggered design described in
"Leveraging staggered tessellation for enhanced spatial resolution in high-granularity calorimeters" NIMA 1060 (2024) 169044

ZDC





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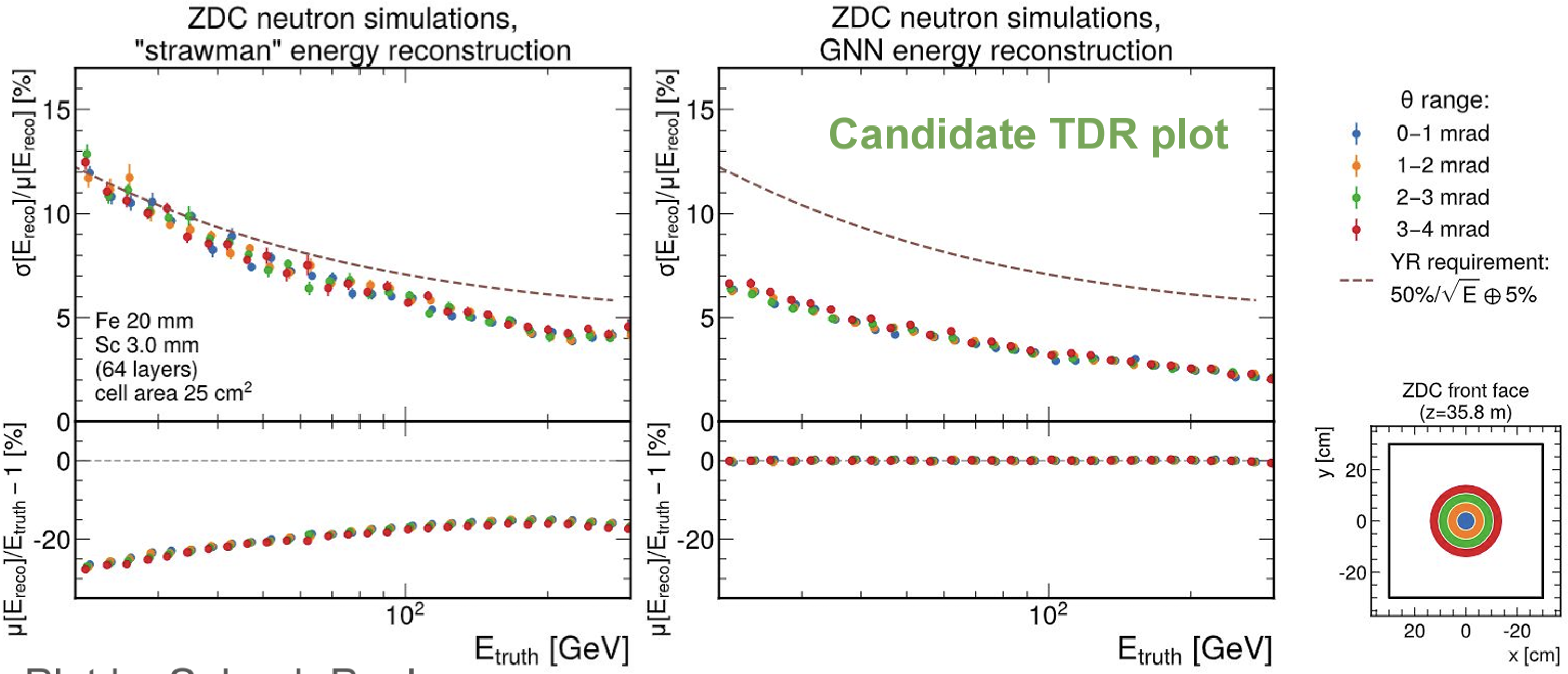
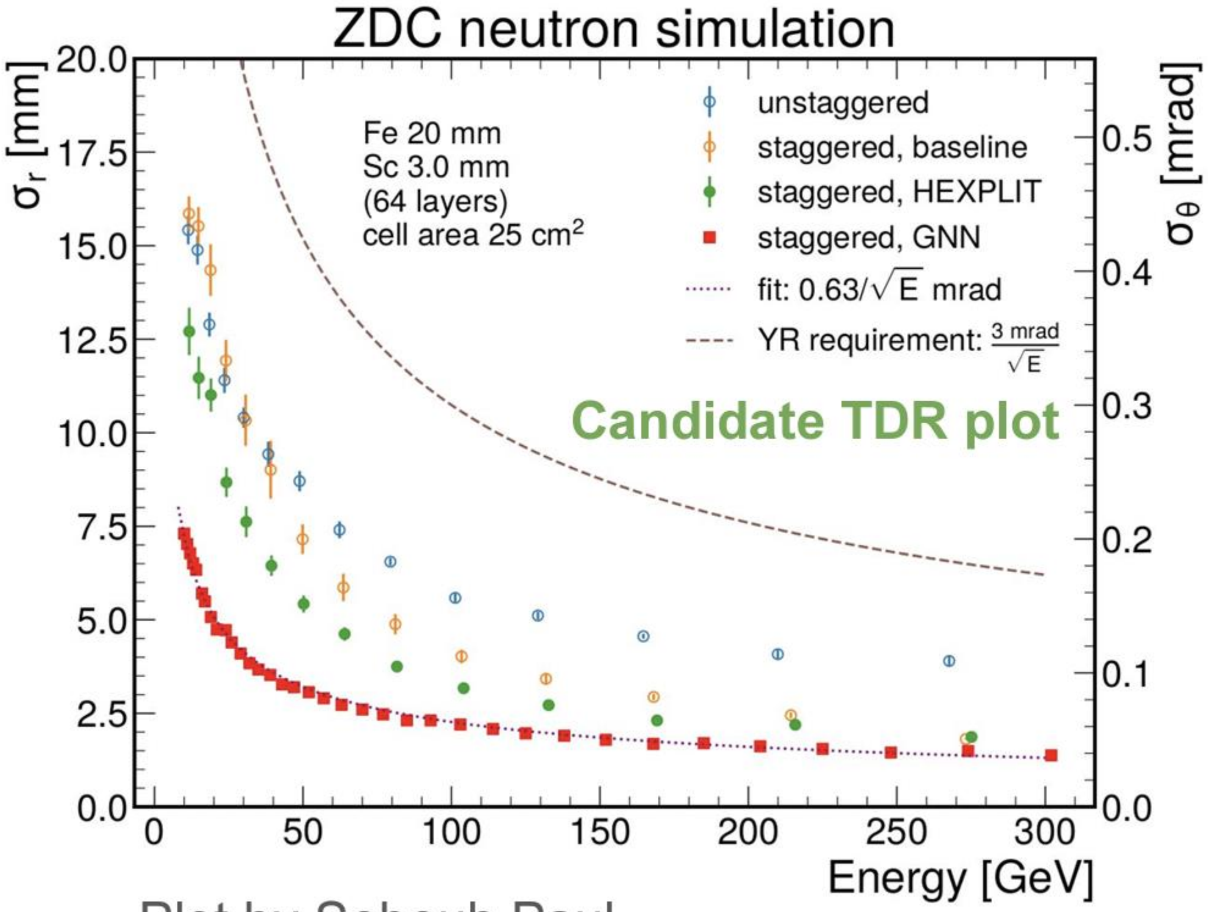


Plot by Sebouh Paul

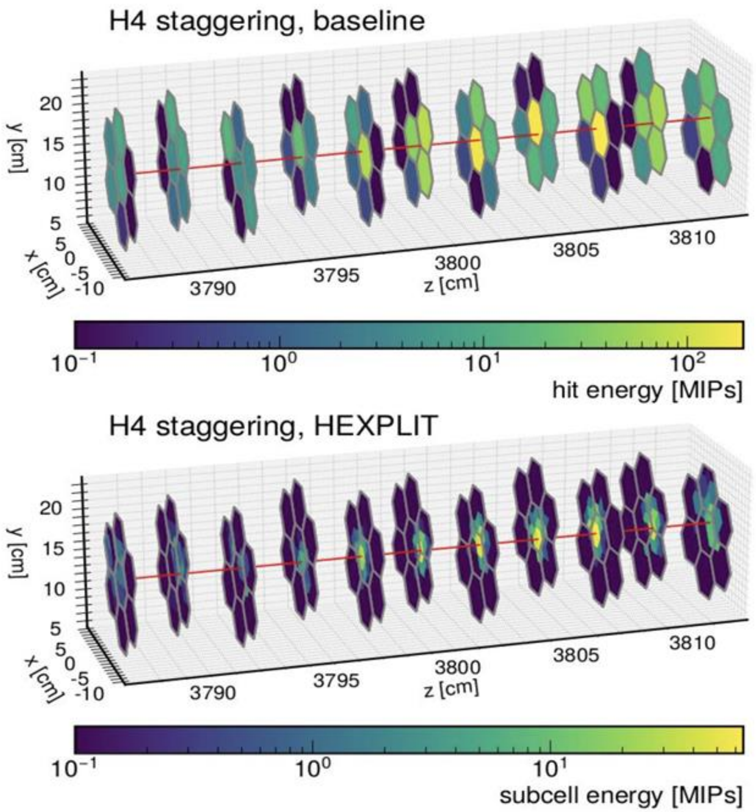
Hadronic Calorimeter – SiPM-on-Tile

Position Resolution



Plot by Sebouh Paul

HEXPLIT design and algorithm described in *"Leveraging staggered tessellation for enhanced spatial resolution in high-granularity calorimeters"* NIMA 1060 (2024) 169044



Brookhaven National Laboratory

Jefferson Lab

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AC-LGAD + readout (EICROC) testing

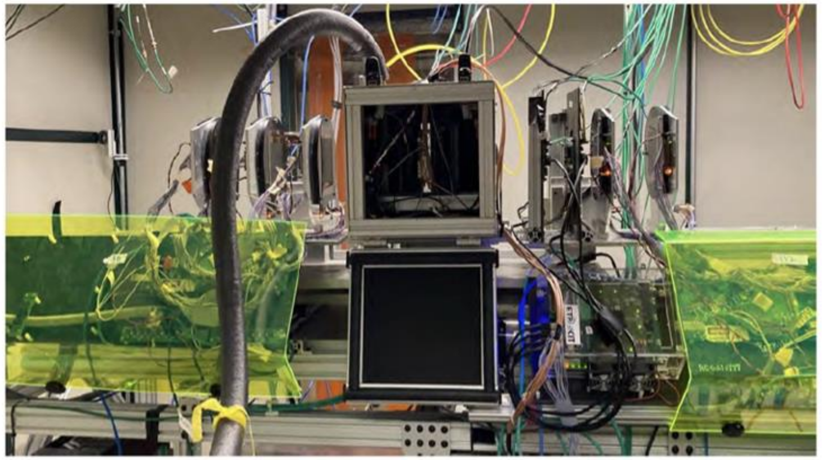
Electron-Ion Collider

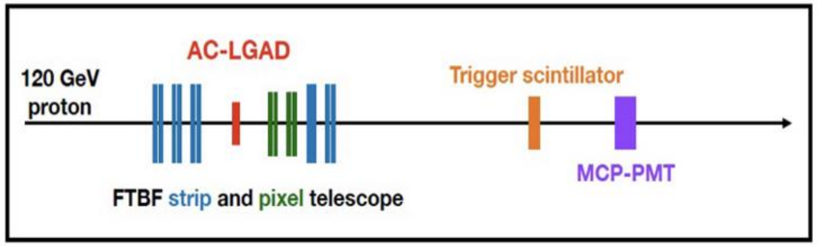
AC-LGAD sensors

- Sensors with different configurations produced by BNL-IO and HPK, and tested with 120GeV protons
- Prototype strip sensors with ~35 ps time resolution and <15 um spatial resolution
- Prototype pixel sensors with ~20 ps time resolution and ~20* um spatial resolution.

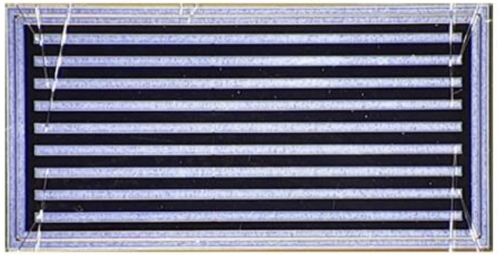
* ~50 um under metal electrodes. To be improved

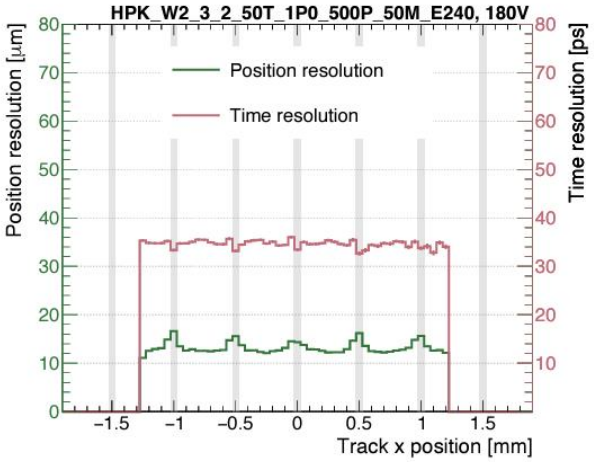
Fermilab Test Beam Setup



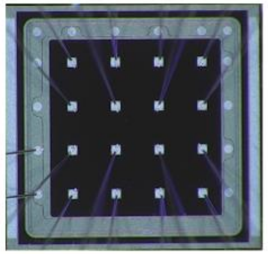


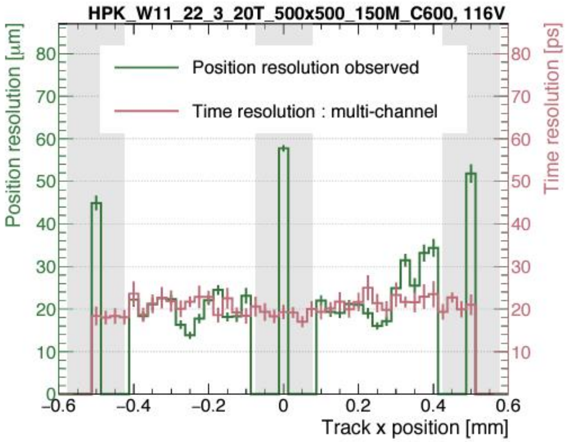
HPK Strip Sensor (4.5x10 mm²)





HPK Pixel Sensor (2x2 mm²)

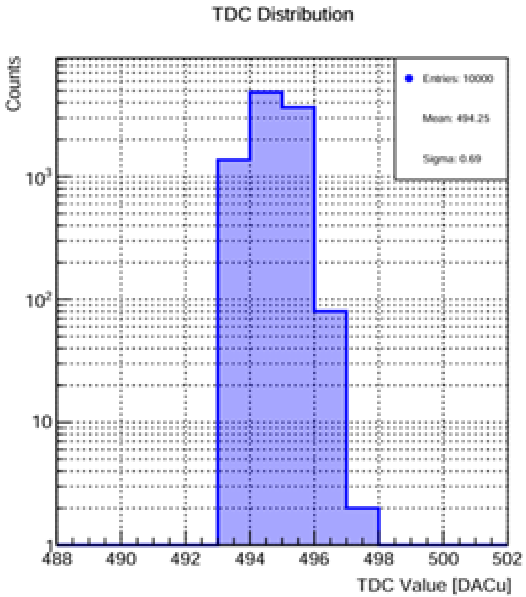




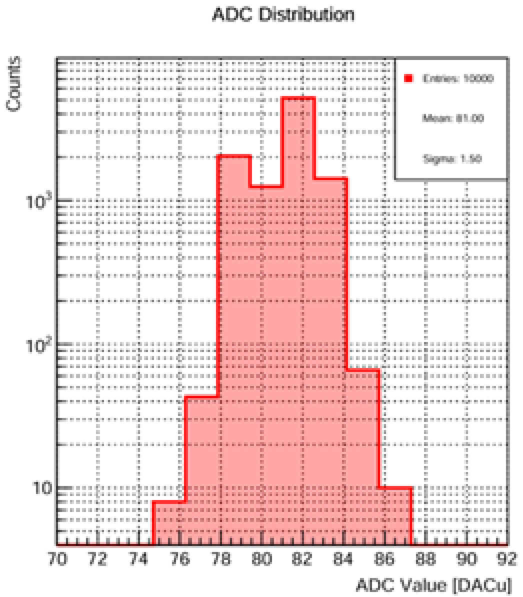
R. Heller, *et al, JINST* **17** P05001 (2022)

ASIC Testing → EICROC v0 (charge injection)

Q = 24 fC

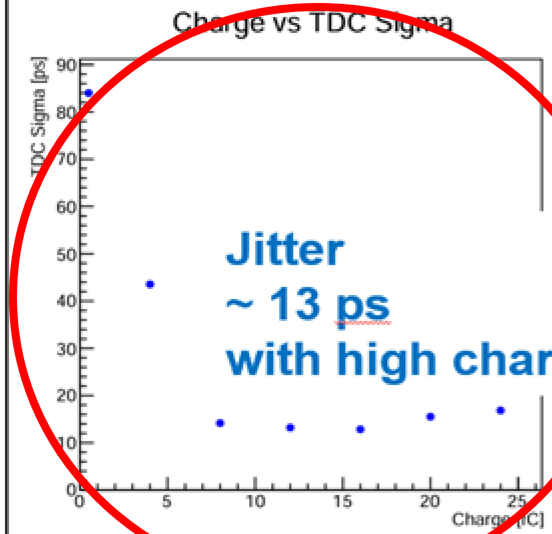


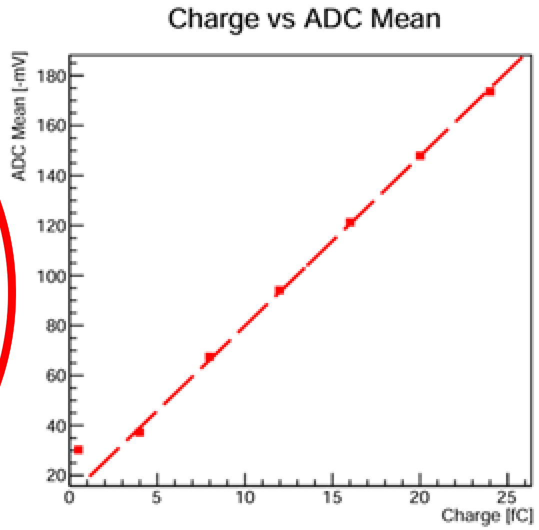
N_event: 10000
Entries: 10000
Mean: 494.25
Sigma(StdDev) : 0.69



N_event: 10000
Entries: 10000
Mean: 81.00
Sigma(StdDev) : 1.50

Charge vs TDC_sigma and ADC_mean





TDC info.
~ 24.4 ps/ 1 unit

ADC info.
~ 1.4 mV / 1 unit
~ (3.75 x DACu – 130) [-mV]

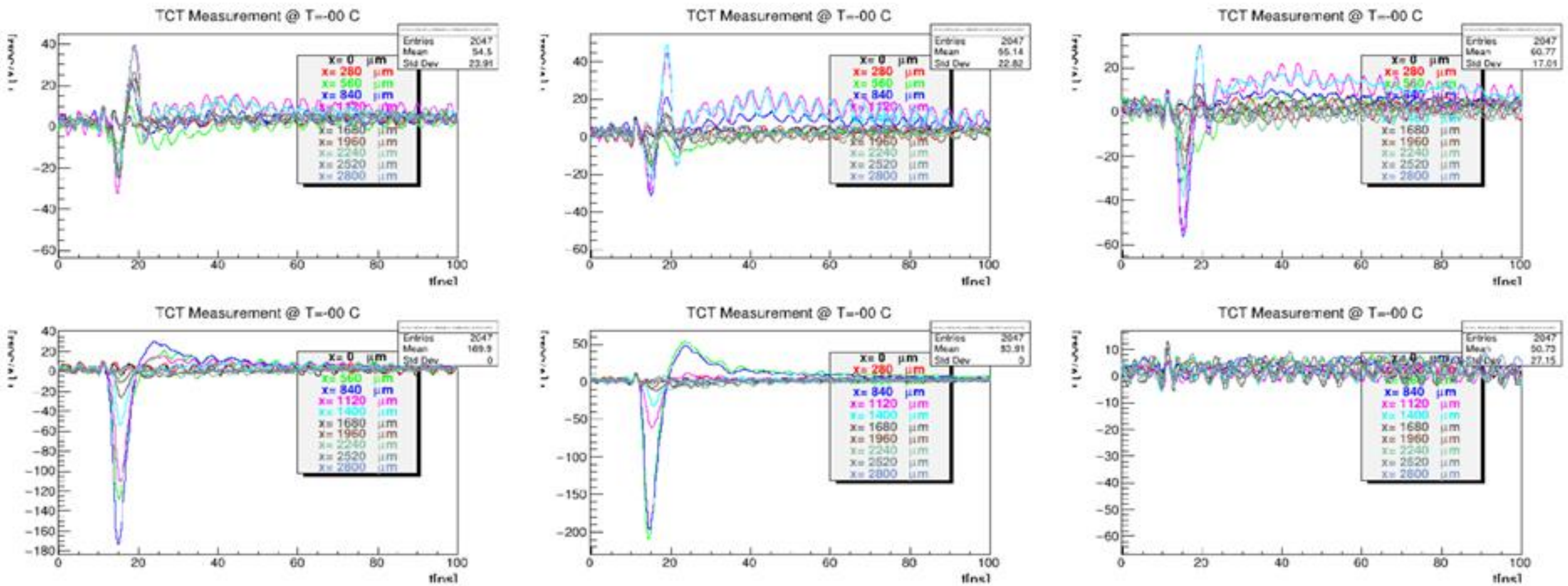
Charge injection info.
~ 0.4 fC / 1DACu, Q = 0.5 – 25 fC

- With analog output measurements, jitter was 7-20ps, depending on whether the clock was turned on (clock worsens the jitter)

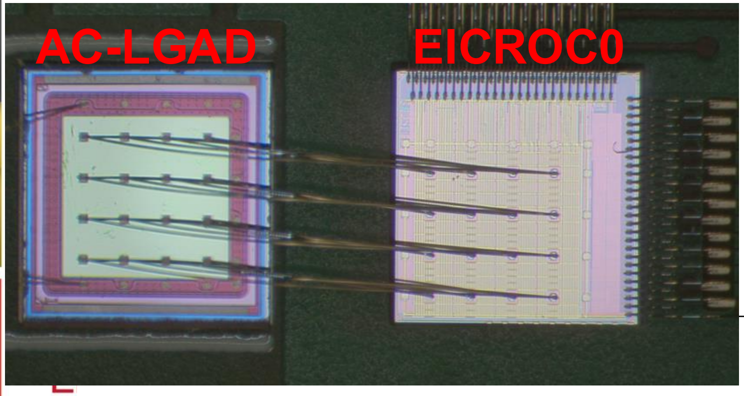
Plots by Kanato Matsutani (Hiroshima)

AC-LGAD Testing → TCT

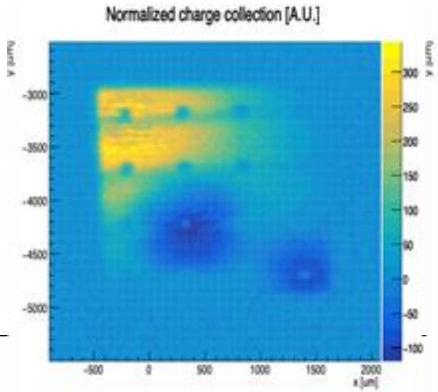
“focused” laser



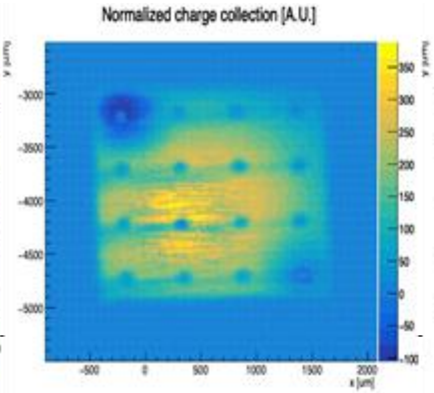
- Each plot is a different region in y, and each curve is a step selection in x – not all steps are shown.
- Plots are in units of current on the y-axis – integrating over the time window provide a charge measurement.
- **Significant amount of noise observed → likely due to wirebonds.**



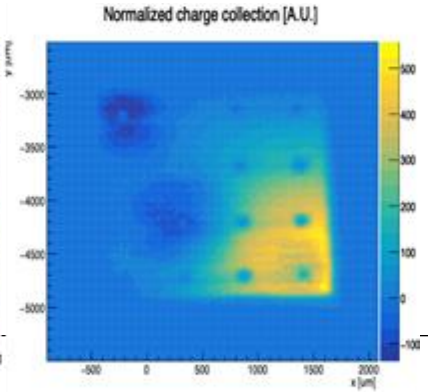
BNL AC-LGAD



Pixel (0,0)



Pixel (2,1)

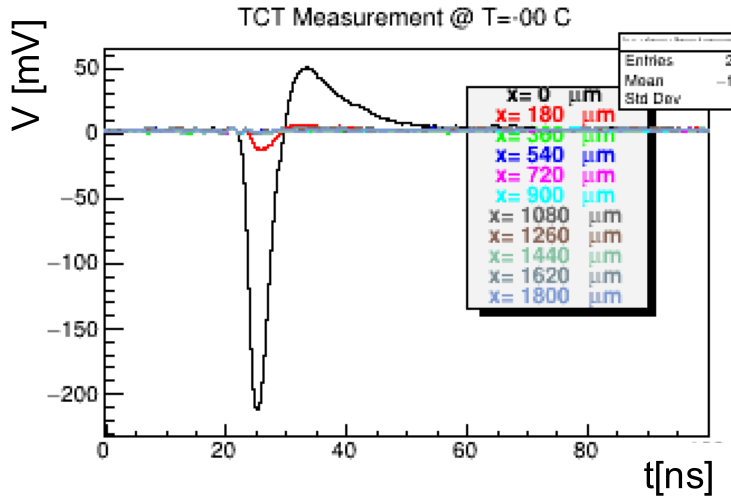


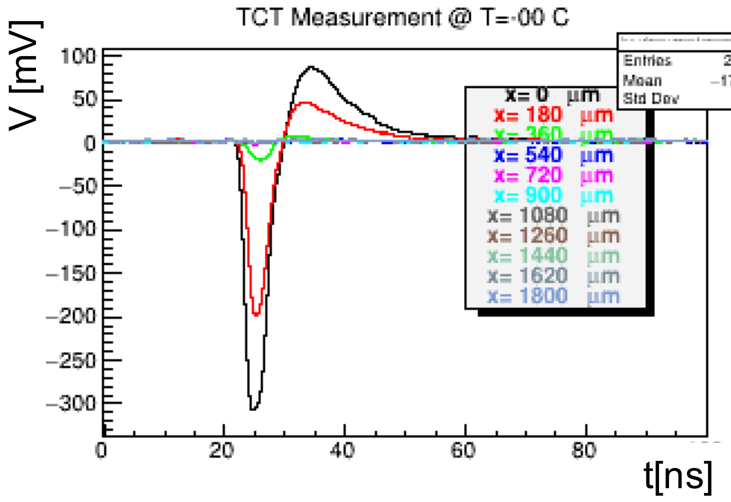
Pixel (3,3)

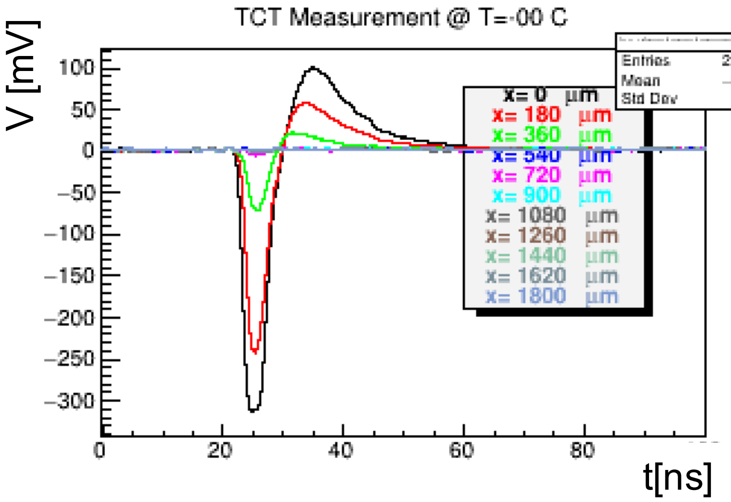
			(0,0)
		(2,1)	
(3,3)			

AC-LGAD Testing → TCT

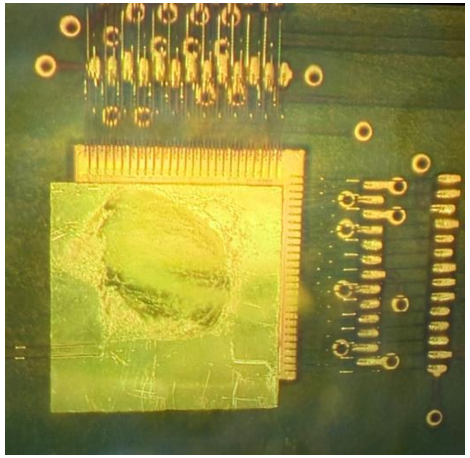
"un-focused" laser



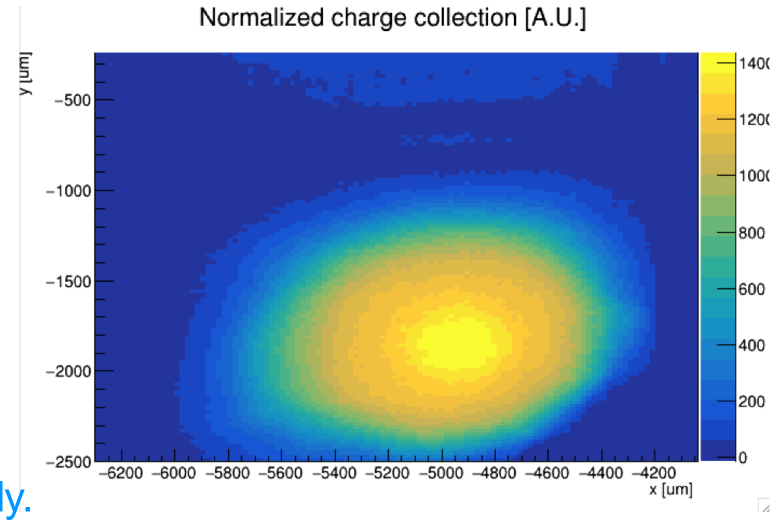




- An AC-LGAD (HPK, 30um) was "etched" to remove portions of the backplane which normally block incident IR light from the laser in a bump-bonded assembly.
  - Etching by Simone Mazza from UCSC.
- Initial tests show promising reduction in noise observed → should be able to make jitter measurements with this setup now.



Etched, bump-bonded assembly.



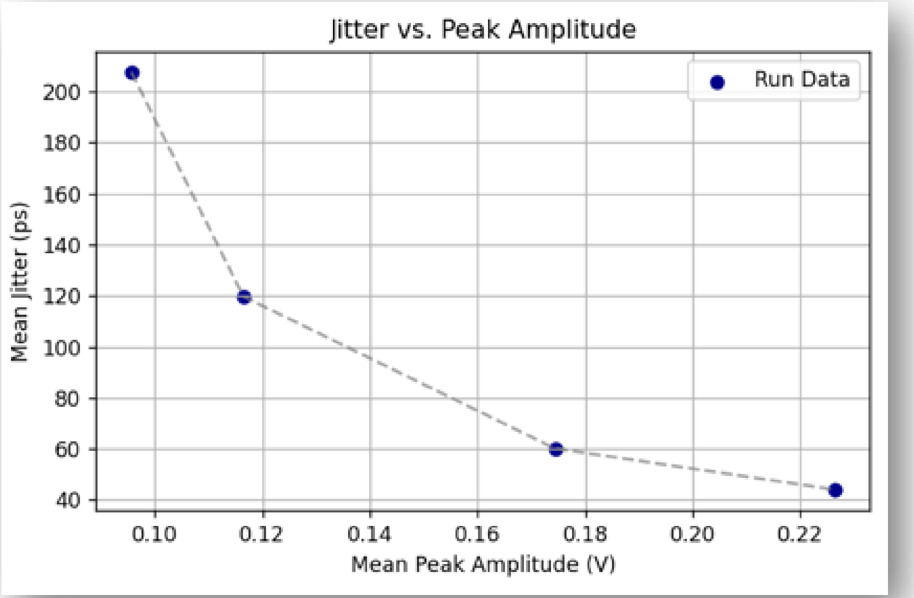
20um steps for TCT

General goals of recent work

- Previous test beams only studied the AC-LGADs themselves → need to understand performance of full system (sensor + ASIC + etc.).
- EICROC is developed specifically for the 500um pitch pixilated AC-LGADs used in ePIC.
  - Based off of architecture in ALTIROC used for DC-LGADs in ATLAS HGTD.
  - Version0 currently in-use (4x4 channel), with new version on the way later this year (full 32x32 channel layout) → final version in ~ 2 years from now.
- Begin by characterizing the timing jitter of the full system → only using analog output of the preamps, updated firmware will allow usage of TDC information for the same studies.
- Next test-beams will be aimed at using the full sensor + ASIC setup → we want to understand performance in the lab first before taking to expensive (and limited) test beam campaigns.

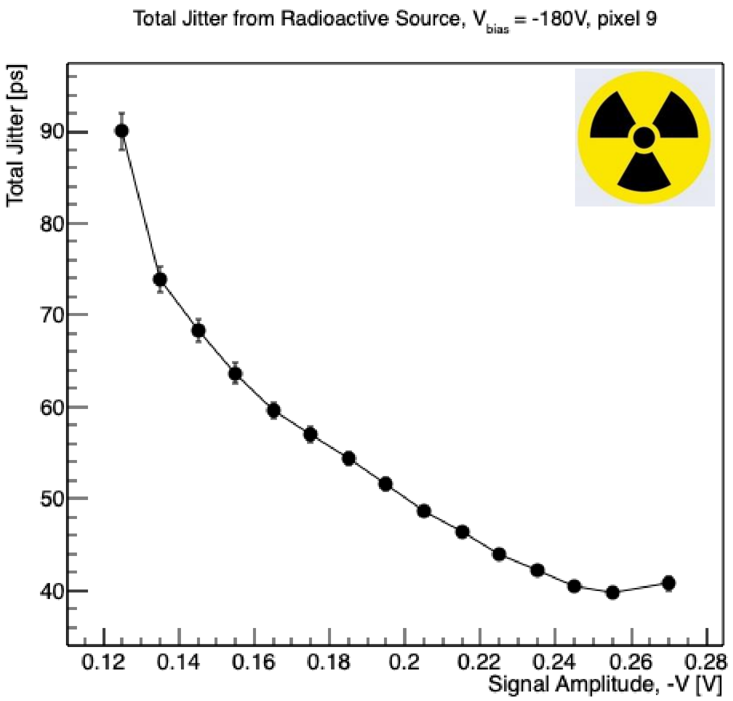
Jitter results

Laser measurements (variable laser power)

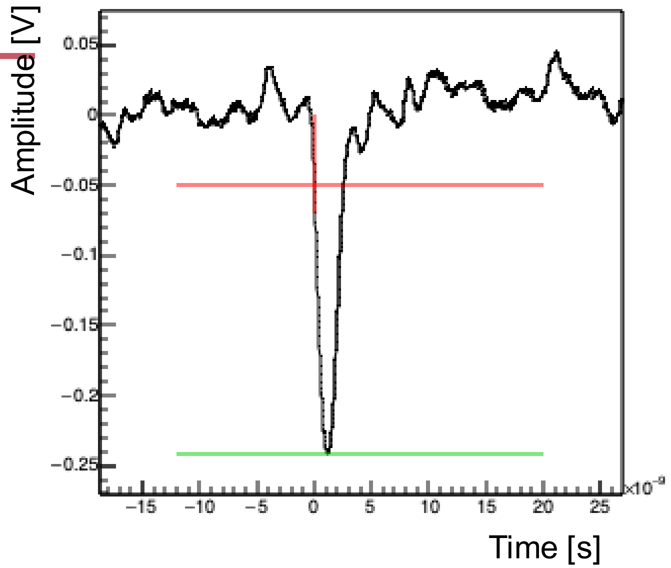


Measurement done by Sergio Garcia-Paravisini (FIU)

DAC Percentage (%)	Mean Peak Amplitude (mV)	Mean Jitter (ps)
72.7%	~90 mV	210 ps
72.4 %	~115 mV	120 ps
72.2 %	~175 mV	60 ps
72%	~210 mV	45 ps



Radioactive source measurements



Jitter measurement done using RMS noise and slewing rate:

$$\sigma_t = \frac{\sigma_{noise}}{\langle dV/dt \rangle}$$

In both cases, total jitter ~ 40ps for the whole system.

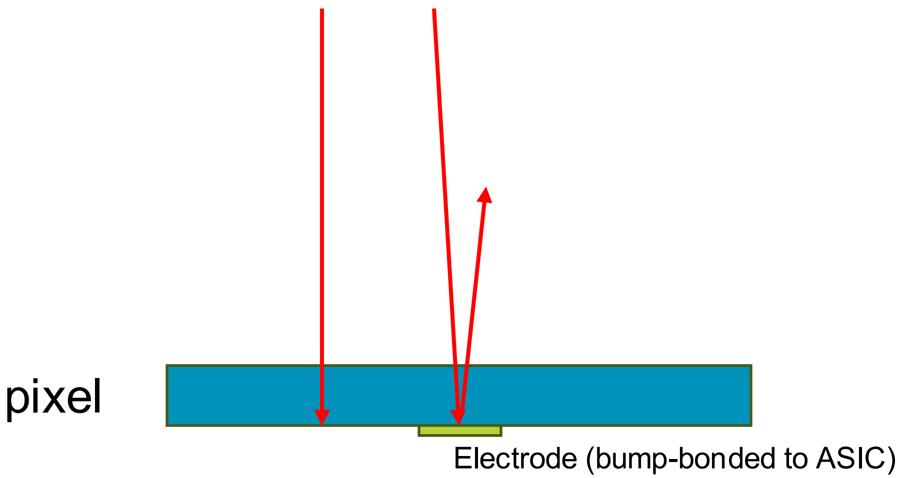
Summary

- ePIC far-forward subsystems are leveraging new technologies to meet EIC physics needs.
- Integration of the subsystems into the beamline a significant challenge → lots of interdependence.
- Cooling systems in early design stage, along with motion systems and supports → depends on the machine, as well, so lots of communication to satisfy all requirements.
- **AC-LGADs**
  - Sensors chosen due to capability to provide precise timing (~35 ps) and spatial resolution (~ 20um, or less).
  - Timing a primary capability of LGADs, in-general (FF has less-stringent requirement compared to TOF).
  - Spatial resolution delivered via charge sharing (500um pixels → normally deliver ~ 140um spatial resolution, previous beam tests show ~20um possible with charge sharing).
    - Especially important for the B0 tracking.
  - Sensors irradiated to 1e15 neutron MEQ → almost no change in gain up to that point, ~ 2-3 orders of magnitude more than expected ePIC irradiation in first 10 years.
  - Power consumption of the ASICs expected to be ~ 1-2 mW/ch (~ 100W upper bound per layer of Roman pots).
- **SiPM-on-tile**
  - Combines standard Fe/scintillator sampling calorimeter with imaging using scintillator-embedded SiPMs.
  - Allows for high precision measurements of energy and position → crucial for neutron-tagged exclusive final states.

Backup

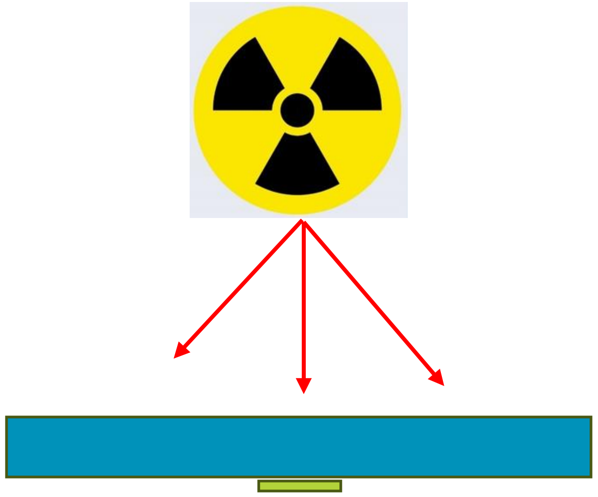
Two independent measurement approaches

Laser TCT system



- Measurement of the the jitter of the laser trigger (measured to be around 9ps).
  - Oscilloscope trigger level set to “best” jitter of the laser.
- Ensure laser is not directly over the electrode.
- Focused laser (spot size < 100um).

Sr-90 source setup

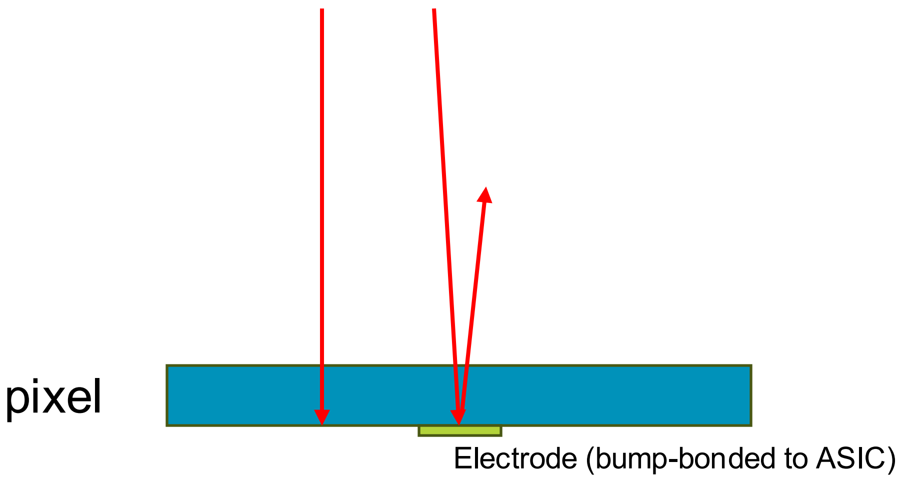


- Trigger threshold set for single pixel to very low value (less than 10% MIP peak).
- Waveforms analyzed to remove multi-peak signals.
- Analysis done in bins of maximum peak amplitude.

Electrode bump-bonded to ASIC

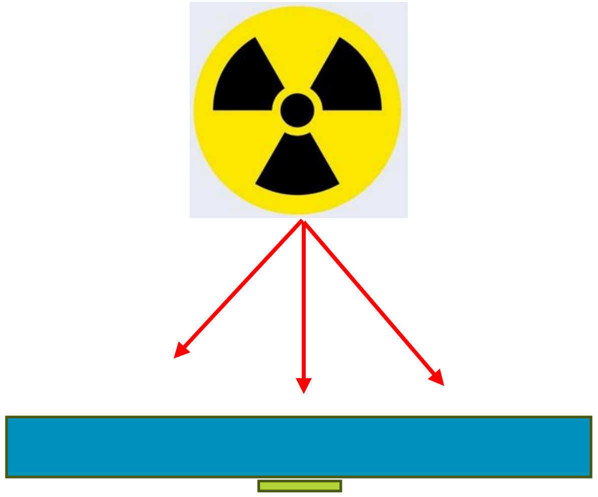
Two independent measurement approaches

Laser TCT system



- **<u>Two methods to calculate jitter</u>**:
  - ➢ Spread of $t_{signal} - t_{trigger}$
    - t_{signal} uses the crossing time at ~50% signal peak.
  - ➢ Using RMS noise and slew rate: $\sigma_{jitter} = \frac{RMS_{noise}}{<\frac{dV}{dt}>}$

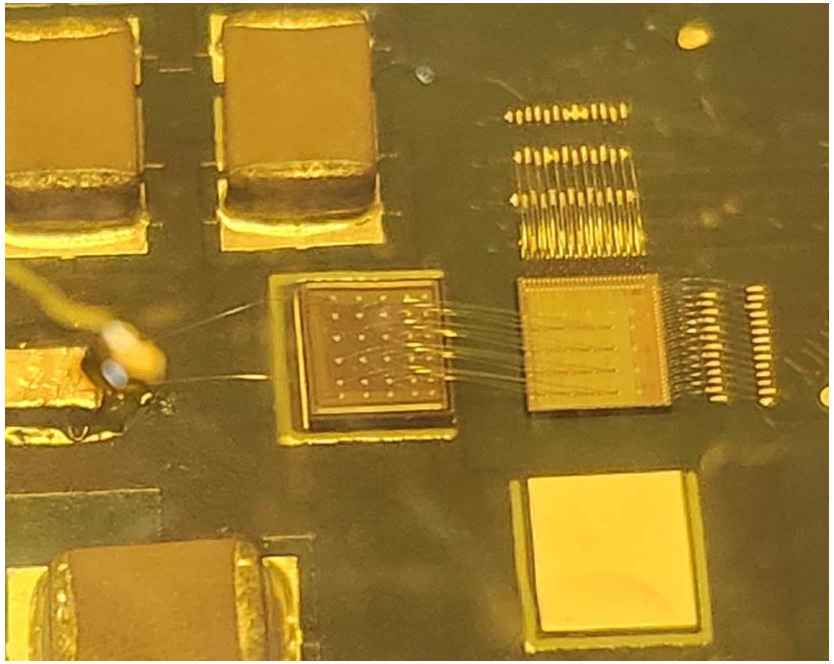
Sr-90 source setup

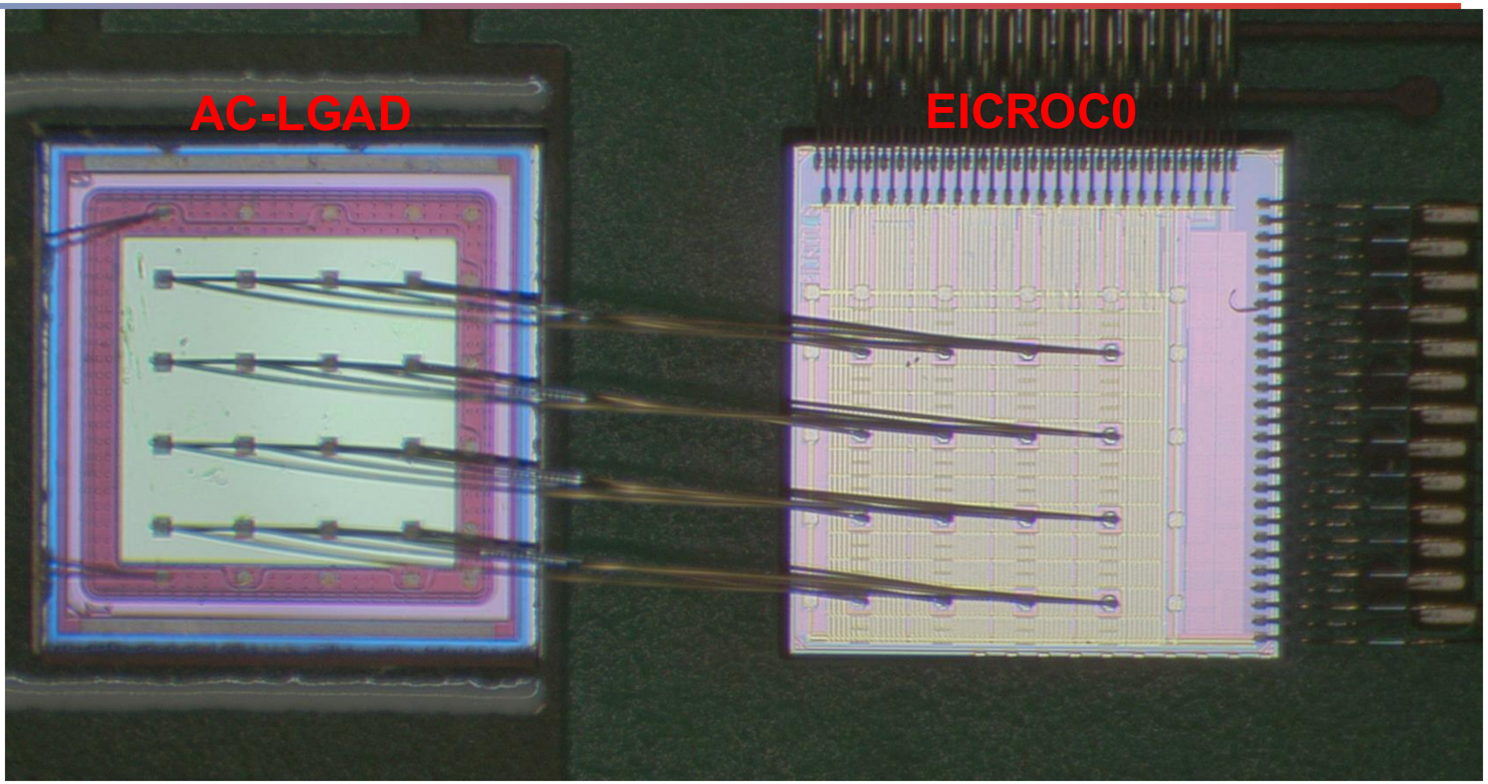


- **<u>One method to calculate jitter</u>**:
  - ➢ Using RMS noise and slew rate: $\sigma_{jitter} = \frac{RMS_{noise}}{<\frac{dV}{dt}>}$

Electrode bump-bonded to ASIC

AC-LGAD Testing



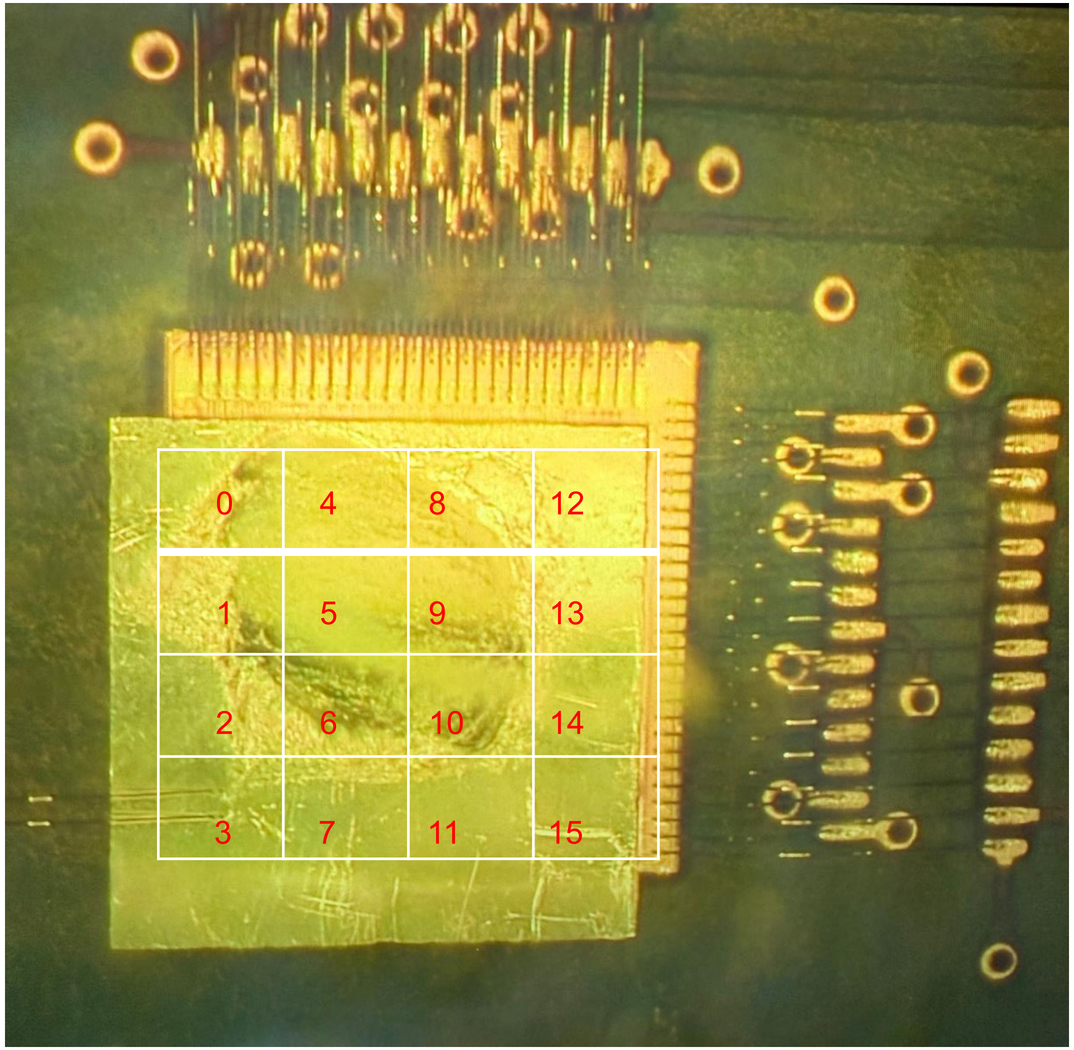


- AC-LGAD sensor (designed and fabricated at BNL) wire-bonded to EICROC0 (OMEGA/ICJLab) for testing on custom test board produced by OMEGA.

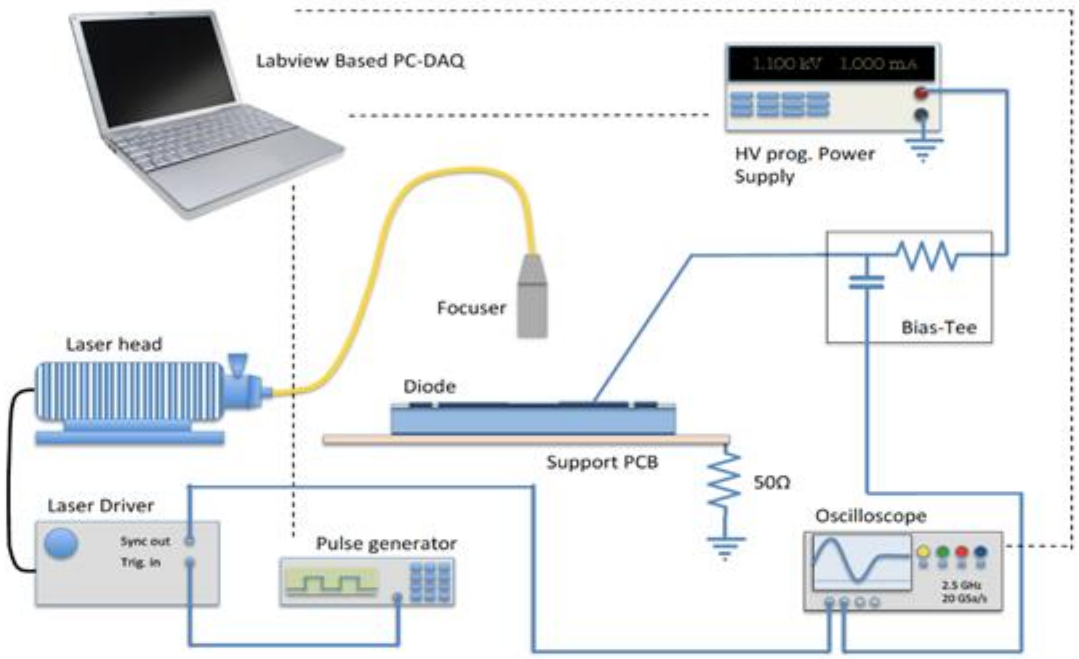
BNL AC-LGAD:

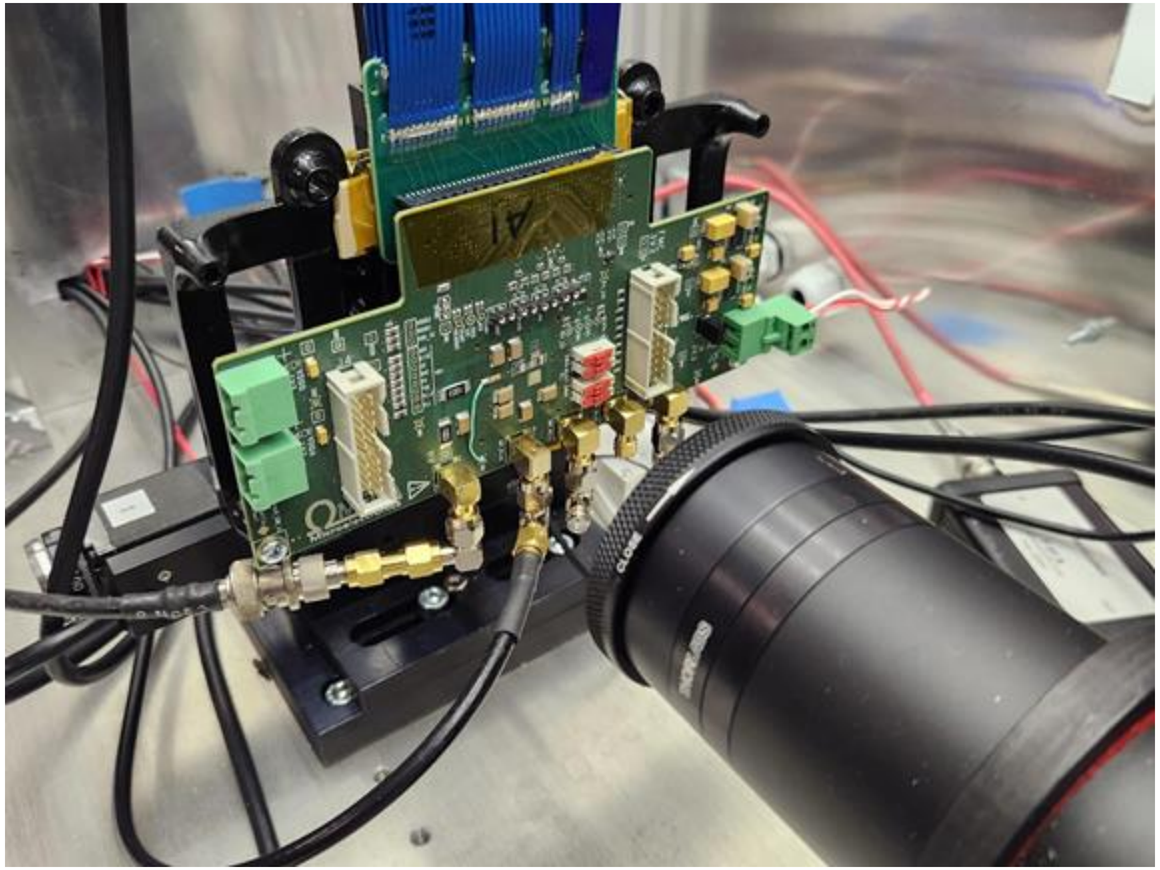
- 500x500 um^2 pixel pitch
- 100x100 um^2 metal electrode
- 30um active thickness

Basic setup (B1 – bump-bonded, etched)



AC-LGAD Testing → AC-LGAD + EICROC0

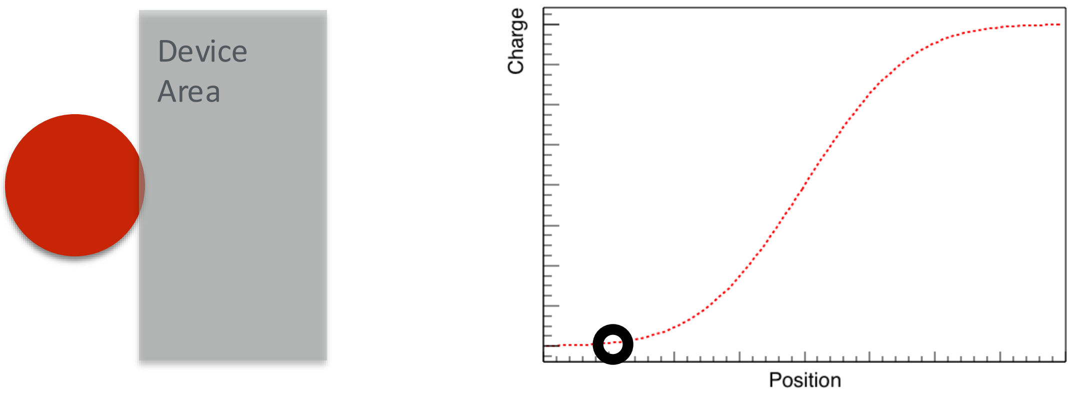




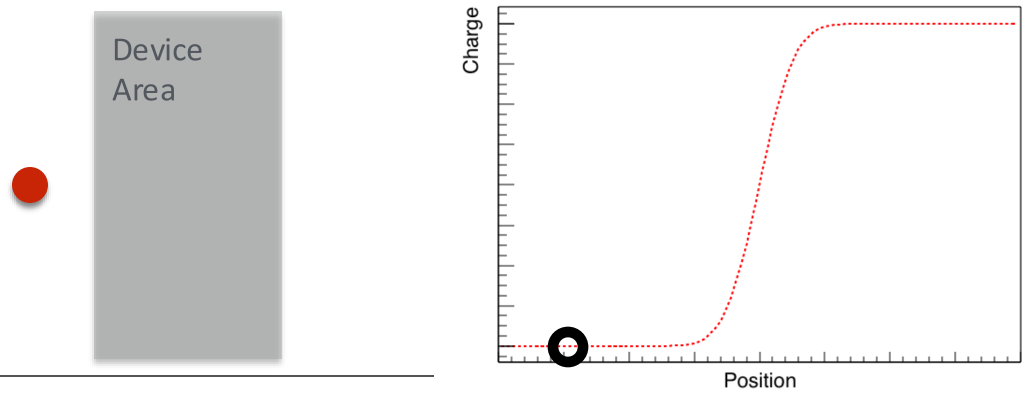
- TCT IR laser scans allow for testing of full sensor + readout with an external trigger (laser).
  - Important to evaluate capabilities of the full chain.
- Radioactive source testing to follow.

Laser Focus

a smaller FWHM of the laser profile indicates a better focus



Non Focused



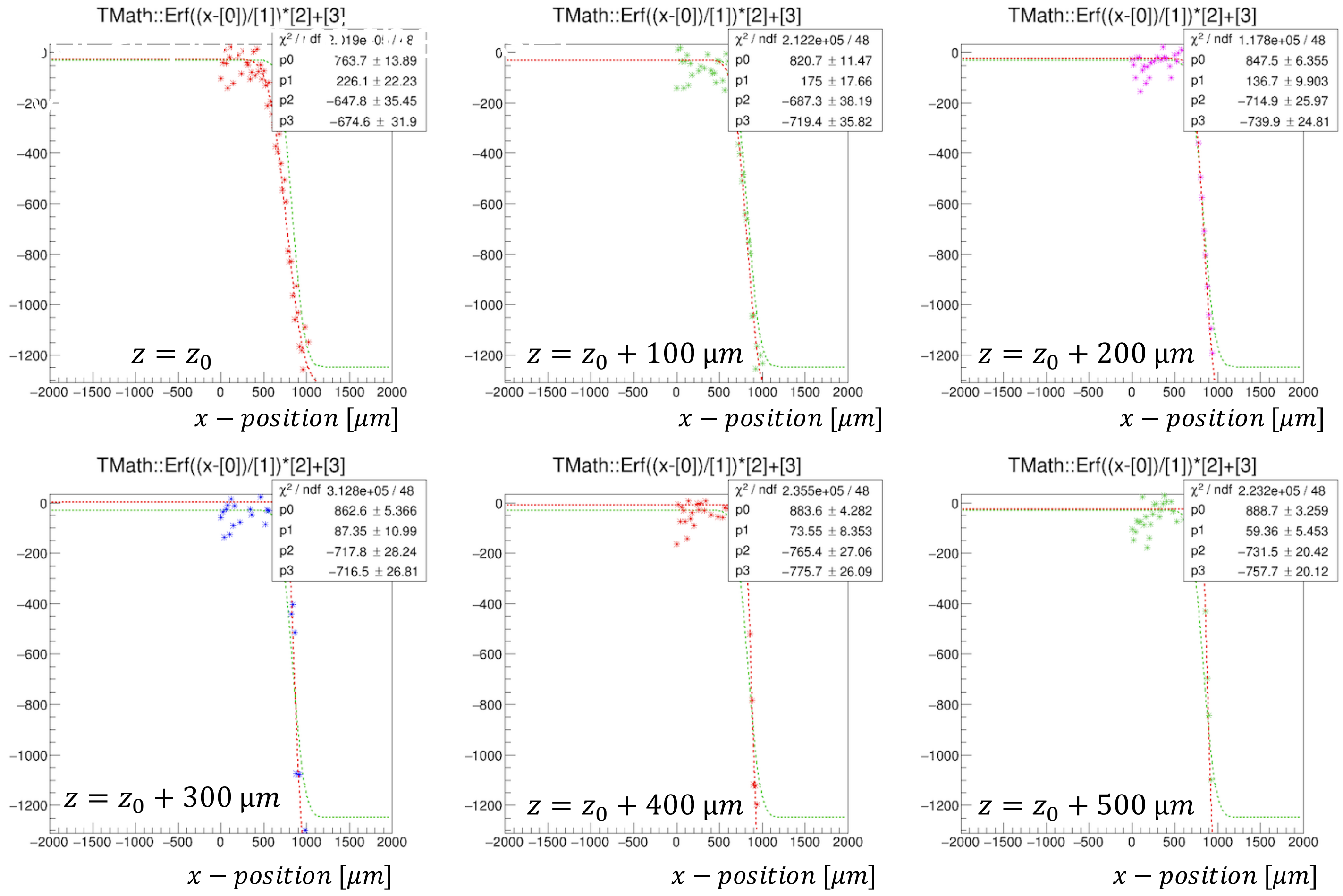
Focused

Animation by Enrico Rossi

Laser Focus

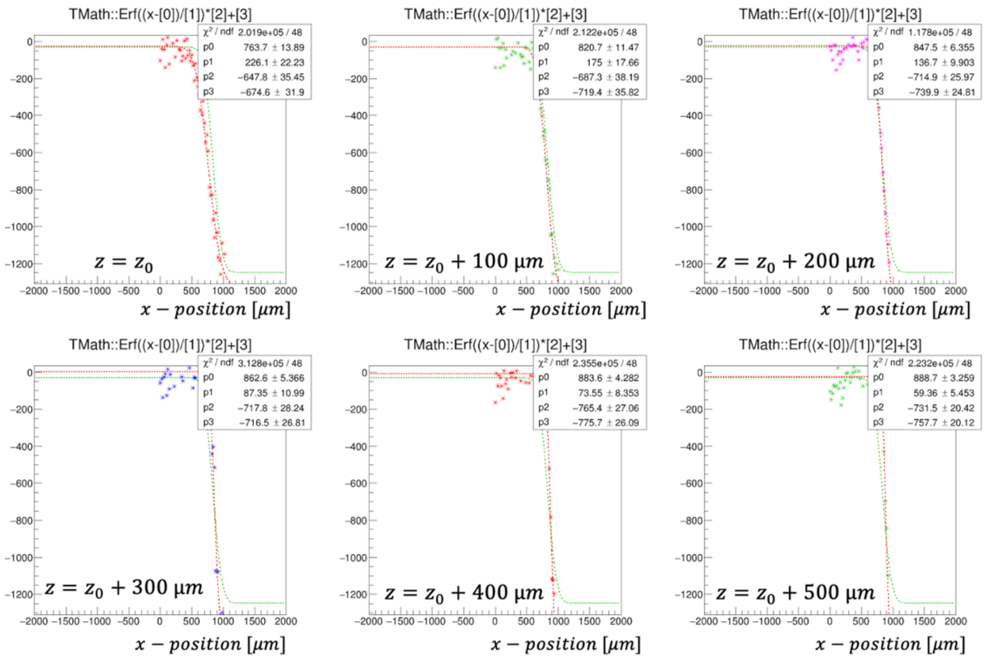
- Scan laser near edge of sensor active area (active pixel).
- Measure integrated charge as a function of transverse position of laser and focal distance.

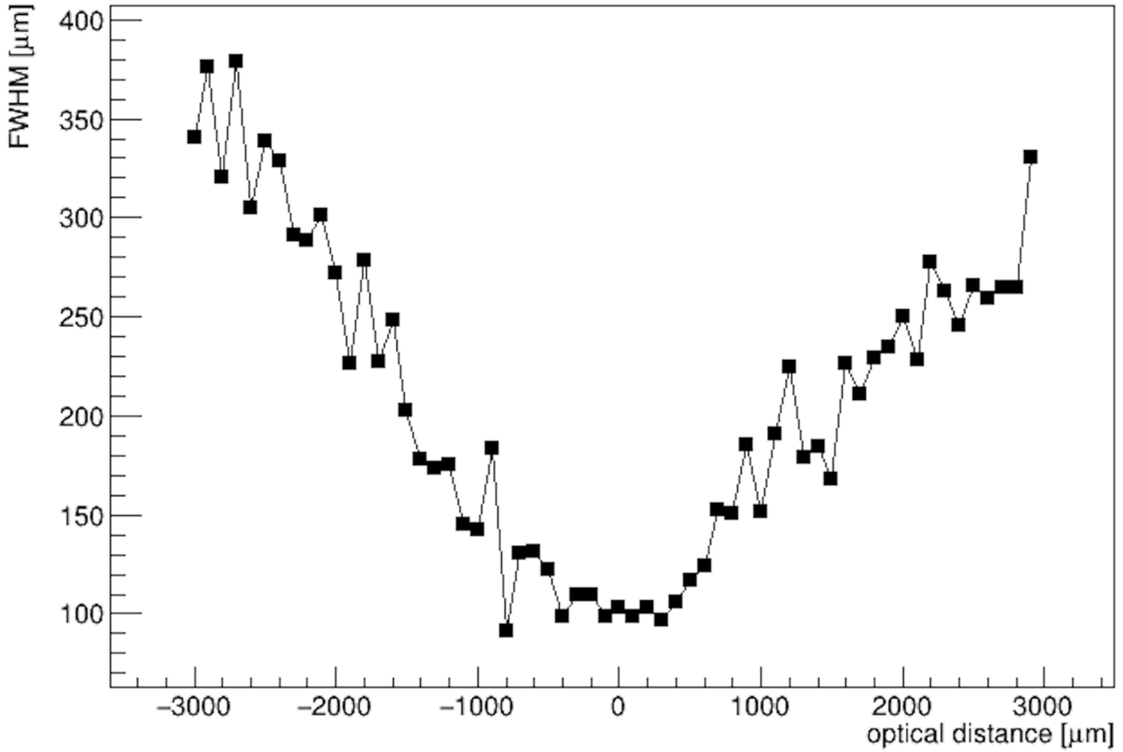
Measure integrated charge as a function of transverse position (the points on the plots), and repeat for each focal distance point (each individual plot).



Laser Focus

- Scan laser near edge of sensor active area (active pixel).
- Measure integrated charge as a function of transverse position of laser and focal distance.
- Fit resulting position dependent distribution with Err function.
- Extract FWHM → minimum is focal point of the laser.
  - Set laser focal distance to this value.



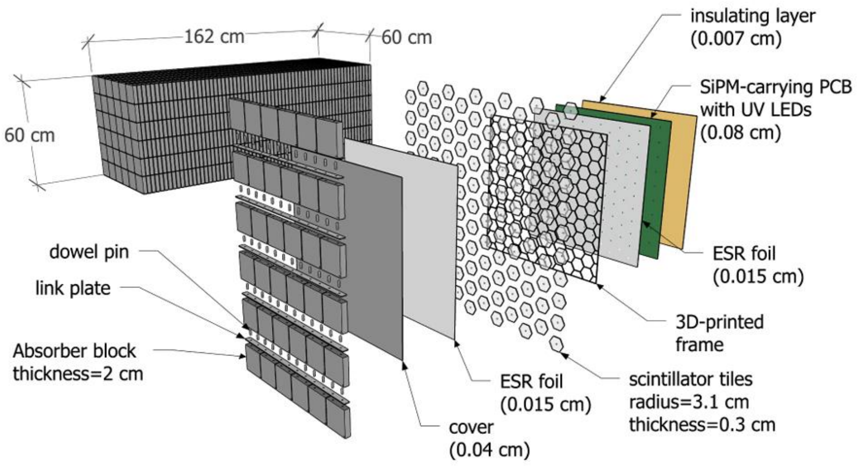


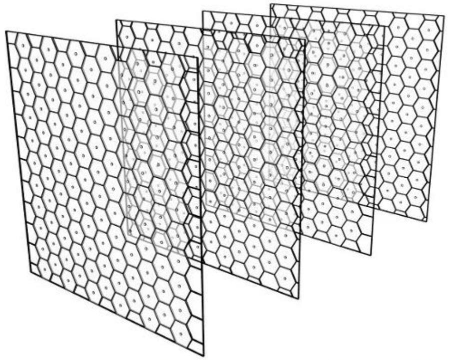
Zero-Degree Calorimeter

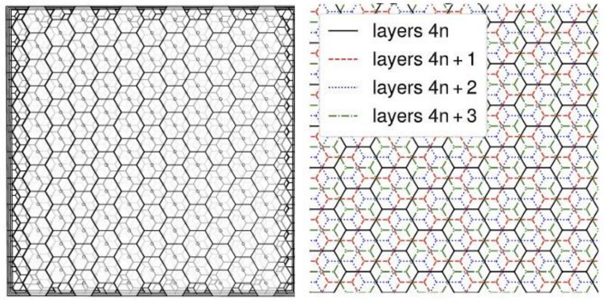
EM Calorimeter – (short) PbWO4

- $PbWO_4$ + SiPM
  - 6x6 array
  - Each crystal: 20.5 x 20.5 x 53.4 mm^3 (6 X_0)
  - ESR reflection layer wrapped by TAC

Hadronic Calorimeter – SiPM-on-Tile







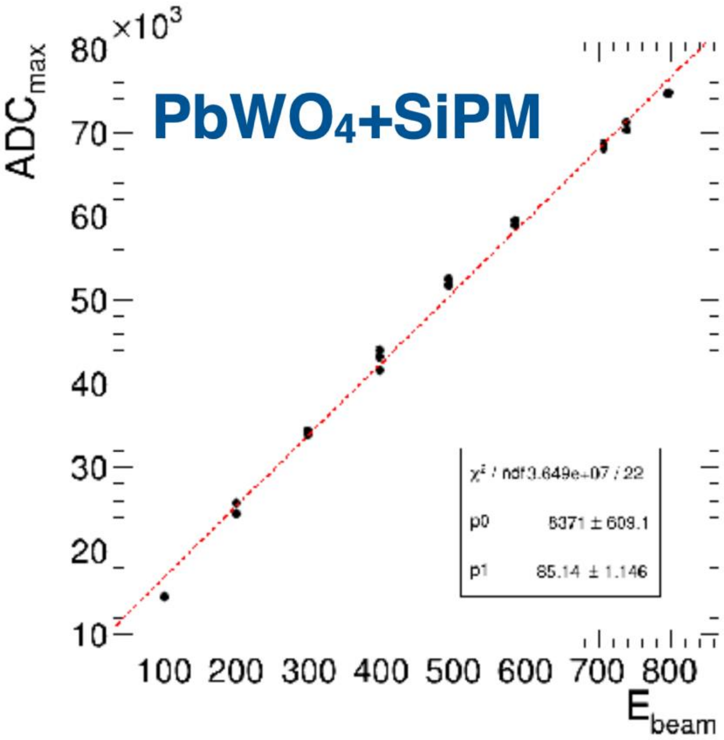
Staggered design described in
"Leveraging staggered tessellation for enhanced spatial resolution in high-granularity calorimeters" NIMA 1060 (2024) 169044

- Leveraging identical technologies for EMCAL ($PbWO_4$ used elsewhere in ePIC) and HCAL (hadron HCAL insert).

Zero-Degree Calorimeter - EMCAL

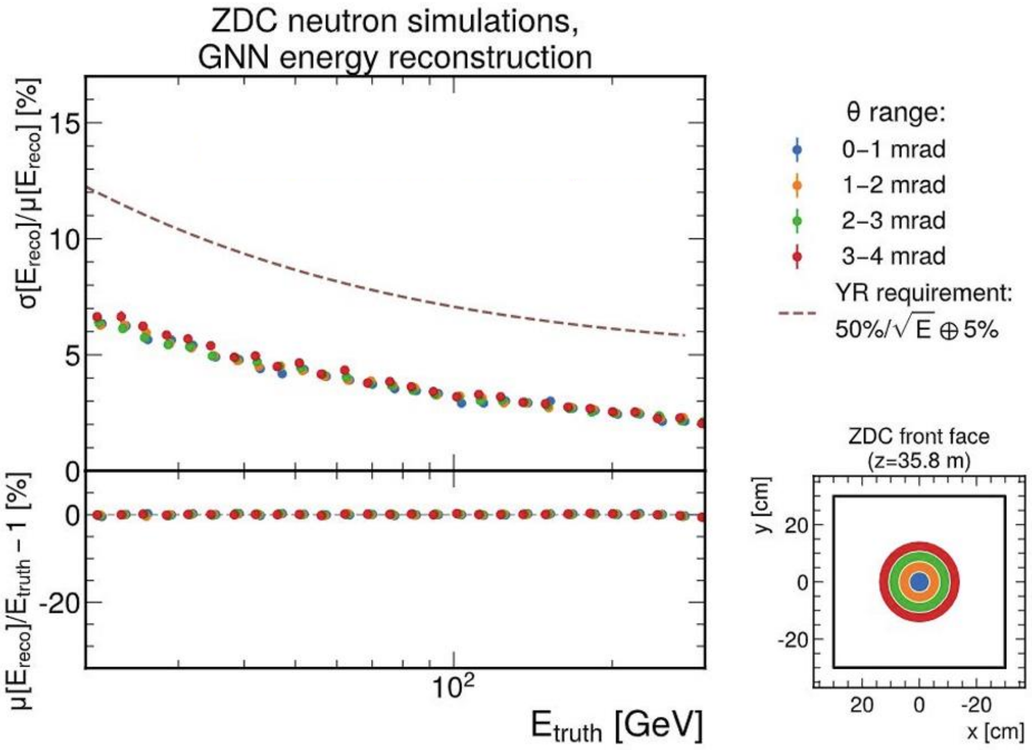
EM Calorimeter – (short) PbWO4

- $PbWO_4$ + SiPM
  - 6x6 array
  - Each crystal: 20.5 x 20.5 x 53.4 mm^3 (6 X_0)
  - ESR reflection layer wrapped by TAC

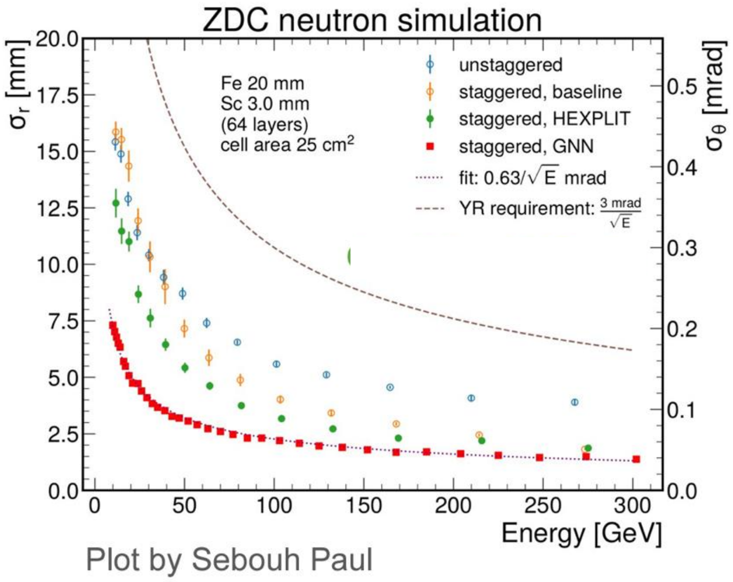


- ZDC EMCAL focused on low-E photons (~ 100 MeV), primarily.
- Beam tests carried out in Japan RARiS facility @ Tohoku Univ.
- Focus is on lower energies since ~100 MeV photons are the primary need for the ZDC crystal EMCAL.

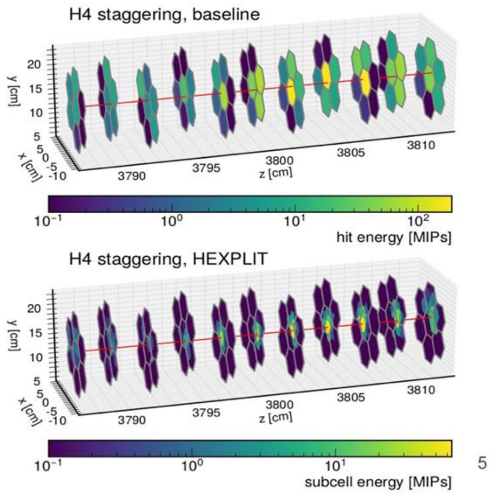
Zero-Degree Calorimeter - HCAL



Position Resolution



HEXPLIT design and algorithm described in *"Leveraging staggered tessellation for enhanced spatial resolution in high-granularity calorimeters"* NIMA 1060 (2024) 169044

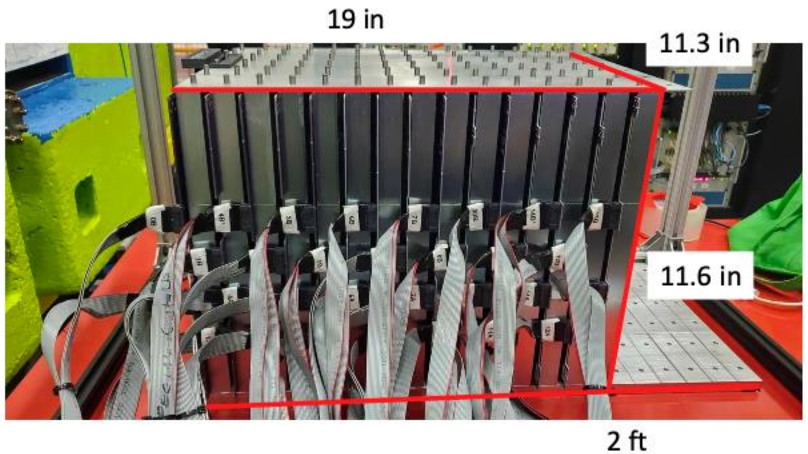


- SiPM-on-Tile concept being used in forward endcap HCAL in ePIC.
- Unique design concept enables "best of both worlds" between standard sampling calorimetry and imaging, but with far less channels.
- Biggest concern is radiation load on ZDC (~ 5e9 neutron equivalent per fb^{-1}) – central SiPMs may need replacement every few years, but design is modular such that replacement should be straightforward.

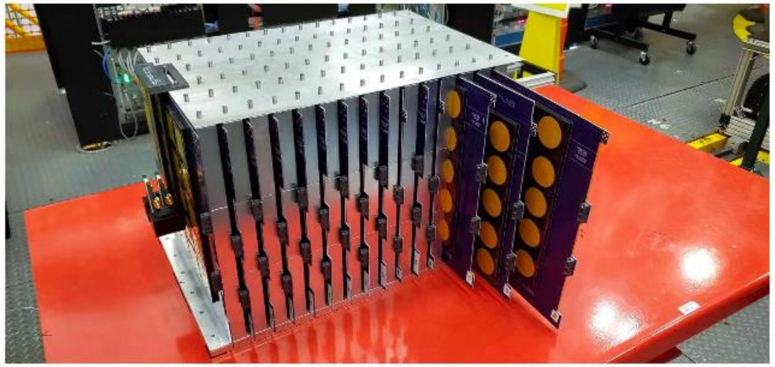
Zero-Degree Calorimeter - HCAL

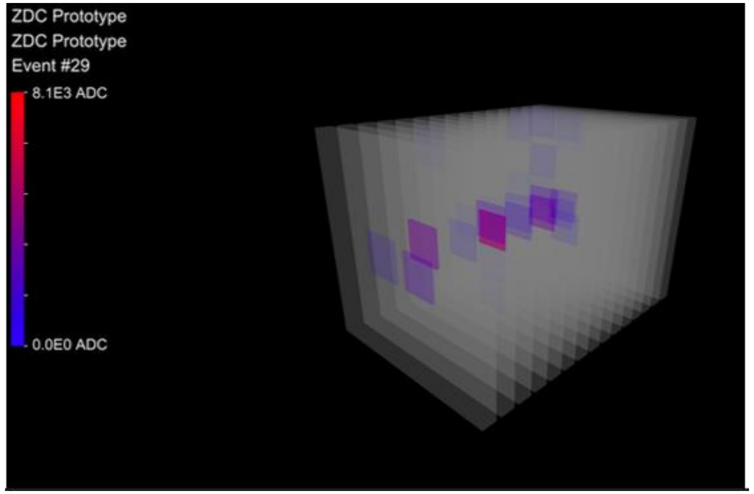
Generation III Test Article Design

- Active area of 29.4cm by 28.8cm (roughly ¼ of the full ZDC transverse size).
- Each layer is 5x5 square scintillating tiles, shifted diagonally every other layer (to create the sub-cells).
- 15 layers, 25 channels per layer = 375 channels.
- 5 dead channels, 98.7% channels functional (no dead channels in the shower core region).
- Test ran from April 23rd to 30th at JLAB.
  - Cosmics collected before testing to perform MIP calibration.
- Irradiation at NASA/BNL NSRL facility to ~ 1e12 1 MEQ fluence.

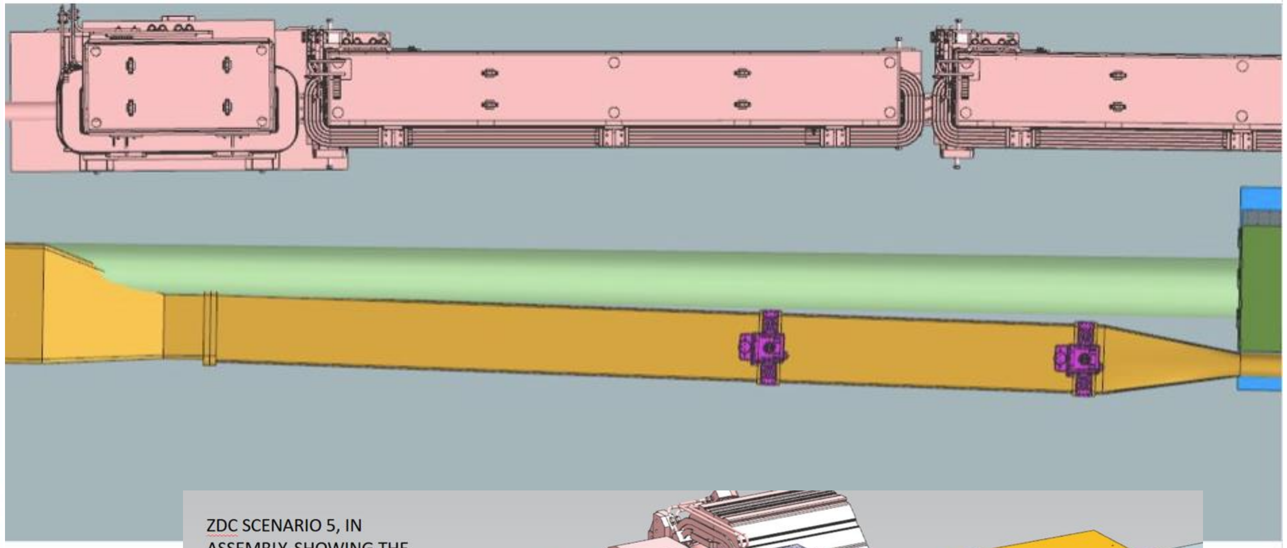


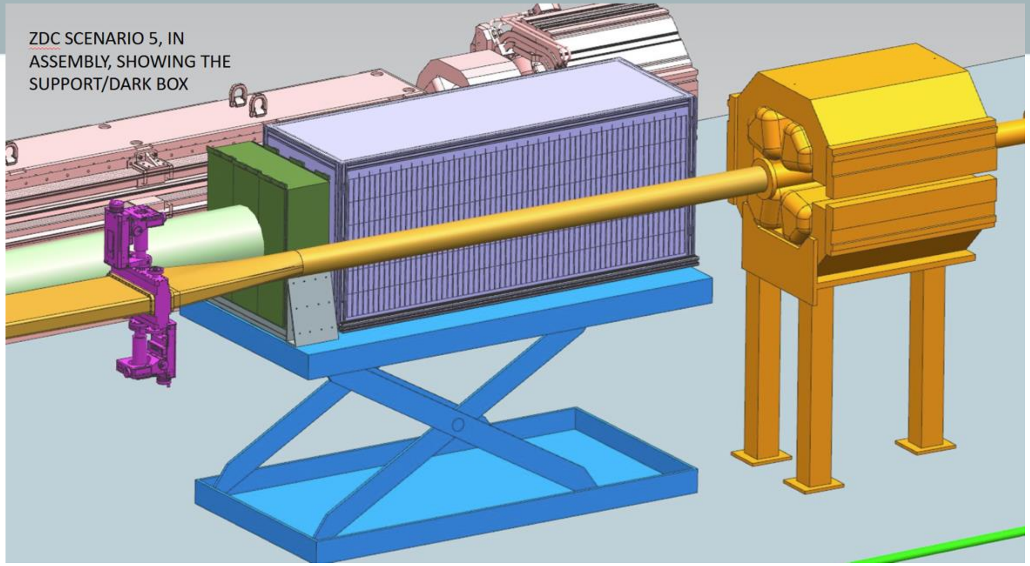
2 cm of iron = 1.1 X_0





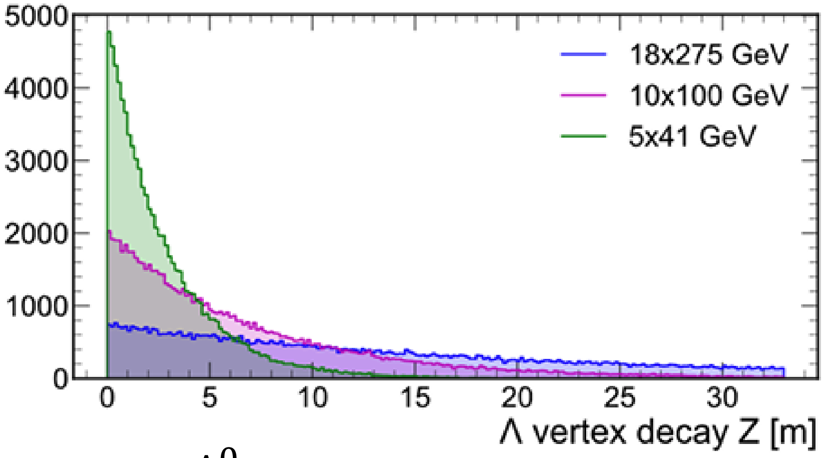
Roman pots/OMD/ZDC Integration





- Accounting for the three particle envelopes with detectors, beam pipes, and hadron beam a challenge.
- **ZDC**
  - Exit window for neutral particles – angled window adds "effective" material $\frac{T_{window}}{\sin(\theta_{incident})}$
  - Incident angles much less than 90 degrees will increase the material (30 degrees increases the thickness by a factor of 2).
  - Work is in progress to finalize this to balance effective thickness of window (needs for vacuum + impedance) with needs for physics.
- **Roman pots and OMD**
  - Integration of sensors + supports in-vacuum poses issues for impedance.
  - Cannot access detector packages without affecting vacuum → put as much outside vacuum as we can (readout, power boards).

Zero-Degree Calorimeter

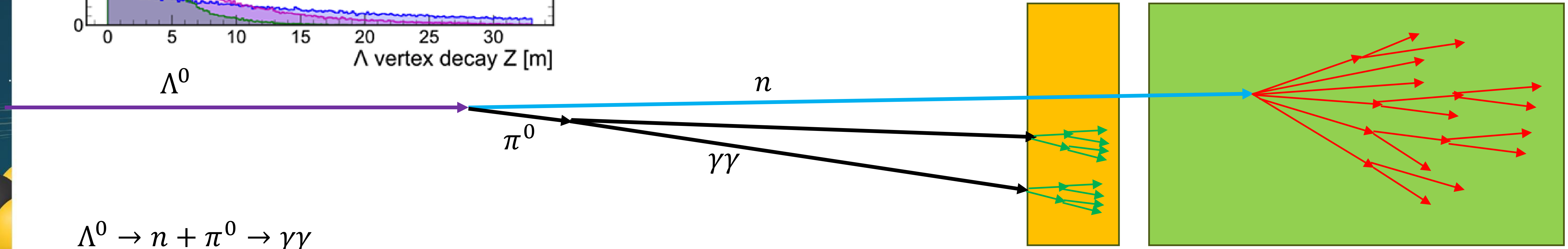


From: J Arrington *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* **48** 075106

Yellow: crystal EMCAL
Green: SiPM-on-Tile

$\Lambda^0 \rightarrow n + \pi^0 \rightarrow \gamma\gamma$

Current configuration (20cm $PbWO_4$)



Shorter crystals (< 7cm $PbWO_4$)